



Lecture 02 - 전력전자공학 기본이론(II)

Prof. Byoung-Kuk Lee, Ph.D.
Energy Mechatronics Lab.
School of Information and Communication Eng.
Sungkyunkwan University

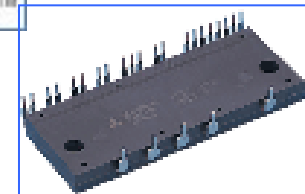
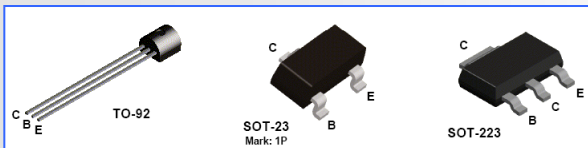
Tel: +82-31-299-4581 Fax: +82-31-299-4612
<http://seml.skku.ac.kr> EML: bkleeskk@skku.edu



Overview (I)

❖ Power Semiconductor Switches?

POWER SEMICONDUCTOR SWITCHING DEVICE



SEMICONDUCTOR
기계적 ↔ 전기적

SWITCHING
DEVICE
 f_{sw} P.D.

POWER
대전류, 고전압
Handling



Overview (II)

❖ 전력용 반도체 스위치의 요구사항

- On state : 전류내량 크고, 도전저항 작을 것
- Off state : 전압내력 크고, 누설전류 작을 것
- On \leftrightarrow Off : 스위칭 시간이 짧을 것
- 스위치 구동 드라이버의 요구 구동전력이 적고, 간단하며, 신뢰성 있을 것

❖ 전력용 반도체 스위치의 분류

- Uncontrollable device : Diode
- Controlled turn-on and Uncontrolled turn-off device : SCR Thyristor
- Controllable device : GTO, Power BJT, MOSFET, IGBT...
- Unipolar voltage-blocking device : Diode, BJT, MOSFET...
- Unipolar voltage-blocking device : SCR, GTO, IGBT...
- Unidirectional current-flow device : Diode, GTO, BJT, MOSFET, IGBT...
- Bidirectional current-flow device : TRIAC...



Overview (III)

❖ Ideal Switch vs. Practical Switch

■ 이상적인 스위치 (Ideal switch)

- On-state : $V_s = 0$; $-\infty < i_s < \infty$
- Off-state : $i_s = 0$; $-\infty < V_s < \infty$
- Switching behavior :

no conversion of energy during
active turn-on/off

■ 실제 스위치 (Practical switch)

- On-state : $V_s \neq 0$; $-\infty < i_s < \infty$ (limited)
- Off-state : $i_s \neq 0$; $-\infty < V_s < \infty$ (limited)
- Switching behavior :

Exist conversion of energy
during active turn-on/off

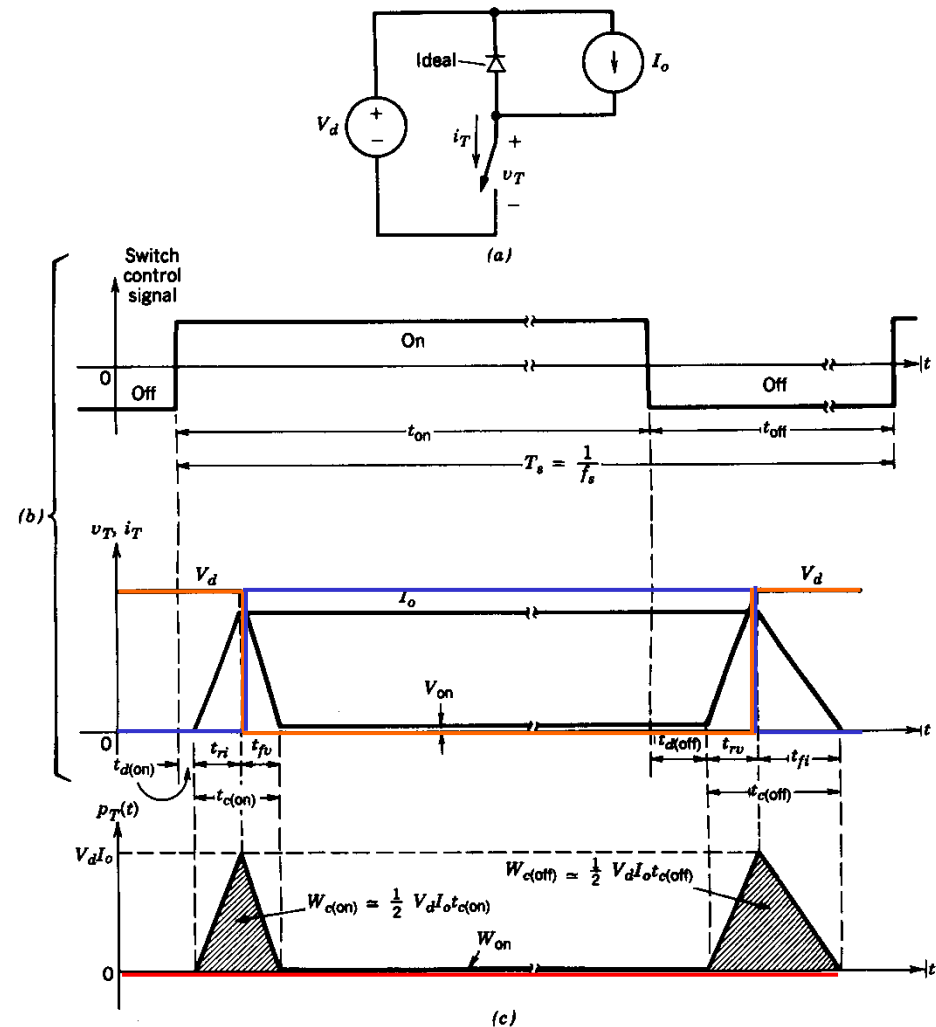
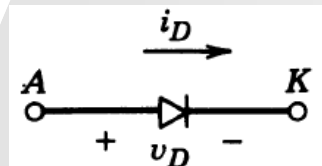


Figure 2-6 Generic-switch switching characteristics (linearized): (a) simplified clamped-inductive-switching circuit, (b) switch waveforms, (c) instantaneous switch power loss.



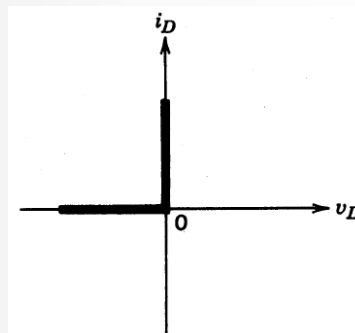
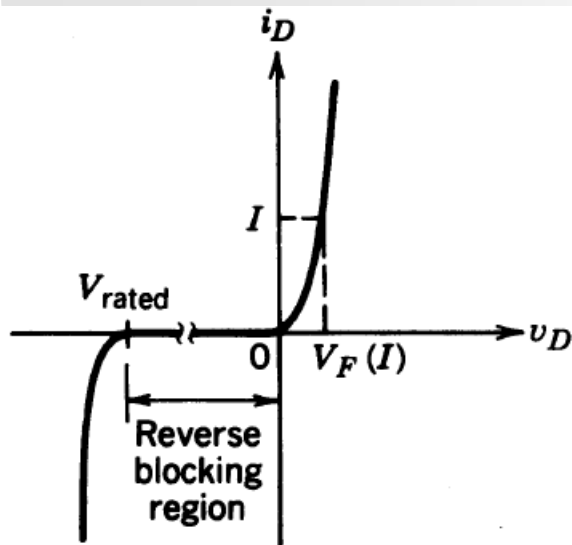
Diode (I)

❖ 심볼



- Uncontrollable device
- PN junction structure

❖ 특성곡선



❖ Datasheet (example)

V_{RSM} V	V_{RRM} V	$I_{FRMS} = 175$ A (maximum value for continuous operation) $I_{FAV} = 100$ A (sin. 180; $T_c = 85^\circ\text{C}$)	
500	400	SKKD 100/04	SKMD 100/04
900	800	SKKD 100/08	SKMD 100/08
1300	1200	SKKD 100/12	
1500	1400	SKKD 100/14	SKMD 100/14
1700	1600	SKKD 100/16	SKMD 100/16
1900	1800	SKKD 100/18	

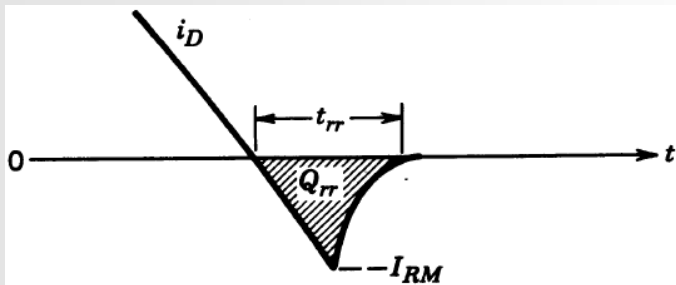
Symbol	Conditions	Values	Units
I_{FAV}	sin. 180; $T_c = 85$ (100) $^\circ\text{C}$	100 (67)	A
I_D	P3/180; $T_a = 45^\circ\text{C}$; B2 / B6	73 / 91	A
	P3/180F; $T_a = 35^\circ\text{C}$; B2 / B6	150 / 190	A
I_{FSM}	$T_{vj} = 25^\circ\text{C}$; 10 ms	2500	A
	$T_{vj} = 125^\circ\text{C}$; 10 ms	2000	A
i_{at}	$T_{vj} = 25^\circ\text{C}$; 8,3 ... 10 ms	31250	A \cdot s
	$T_{vj} = 125^\circ\text{C}$; 8,3 ... 10 ms	20000	A \cdot s
V_F	$T_{vj} = 25^\circ\text{C}$; $I_F = 300$ A	max. 1,35	V
$V_{(TO)}$	$T_{vj} = 125^\circ\text{C}$	max. 0,85	V
r_T	$T_{vj} = 125^\circ\text{C}$	max. 1,3	m Ω
I_{RD}	$T_{vj} = 125^\circ\text{C}$; $V_{RD} = V_{RRM}$	max. 5	mA
$R_{th(j-c)}$	per diode / per module	0,35 / 0,175	K/W
$R_{th(o-s)}$	per diode / per module	0,2 / 0,1	K/W
T_{vj}		- 40 ... + 125	$^\circ\text{C}$
T_{stg}		- 40 ... + 125	$^\circ\text{C}$
V_{isol}	a. c. 50 Hz; r.m.s.; 1 s / 1 min.	3600 / 3000	V~
M_s	to heatsink	5 \pm 15 %	Nm
M_t	to terminals	3 \pm 15 %	Nm
a		5 * 9,81	m/s 2
m	approx.	95	g
Case	SKKD	A 10	
	SKMD	A 33	



Diode (II)

❖ 특성

▪ Reverse recovery



- Fast-recovery diodes have a small reverse-recovery time
- Using fast switching frequency in case of dc-dc converter

❖ 종류

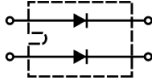
- General purpose diode (rectifier diode)
- Zener diode
- Fast recovery diode
- Ultra fast diode
- Schottky diode
- LED
- Photo diode...

IXYS

Fast Recovery
Epitaxial Diode (FRED)

DSEI 2x 61 $I_{FAVM} = 2 \times 71 \text{ A}$
 $V_{RRM} = 200 \text{ V}$
 $t_{rr} = 35 \text{ ns}$

V_{RRM} V	V_{FWM} V	Type
200	200	DSEI 2x 61-02A



miniBLOC, SOT-227 B
E72873

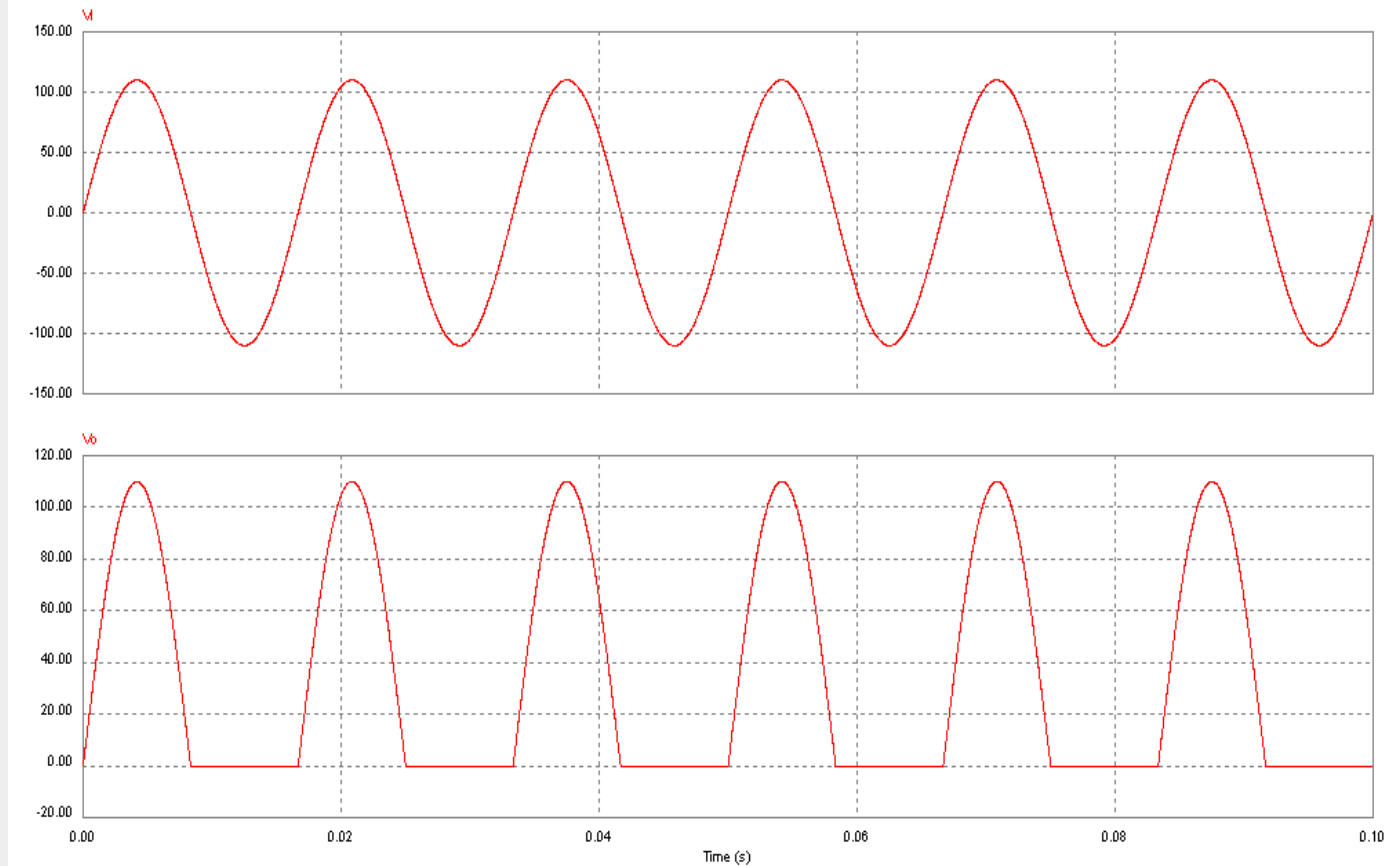
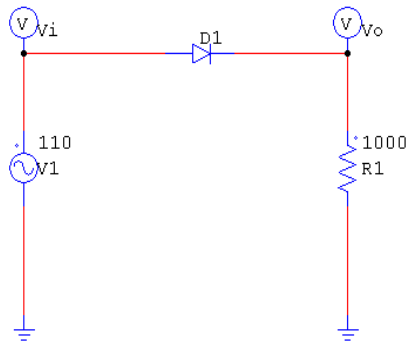


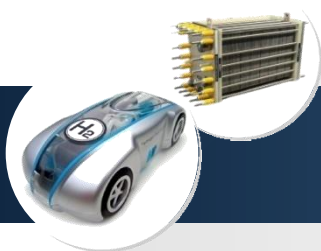
❖ 응용분야 (→ 종류)



Diode (III)

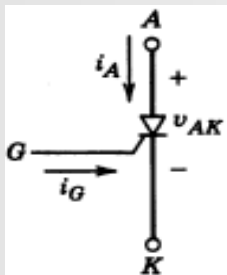
❖ PSIM 시뮬레이션





Thyristor (I)

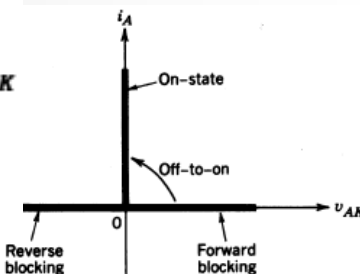
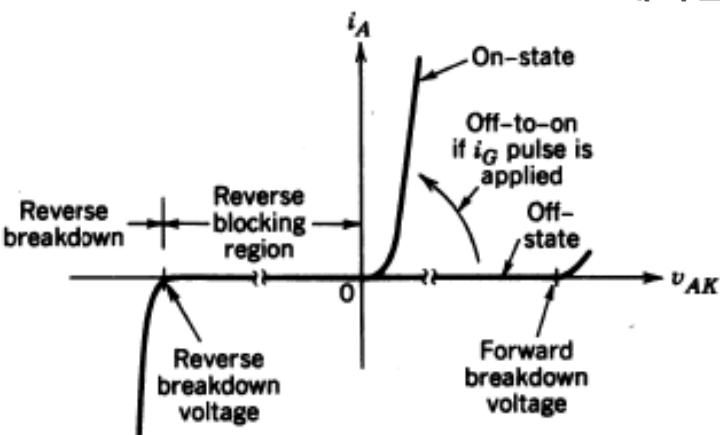
❖ 심볼



❖ 특성곡선

- Current controlled device
- Low switching frequency
- Uncontrollable gate turn off
- High volt. and curr. capab.

- 문턱전류 (Holding current) – (I_H)
- 유지전류 (Latching current) - (I_L)
- Turn-on 제어만 가능



❖ Datasheet (example)

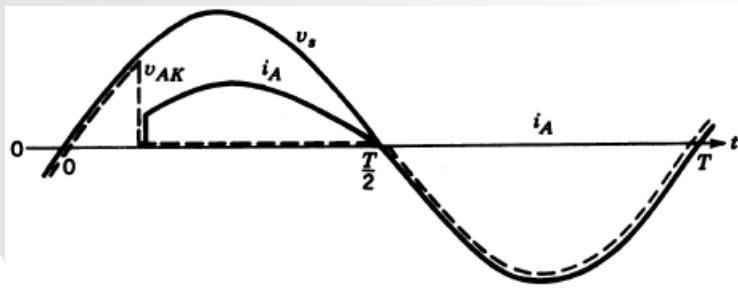
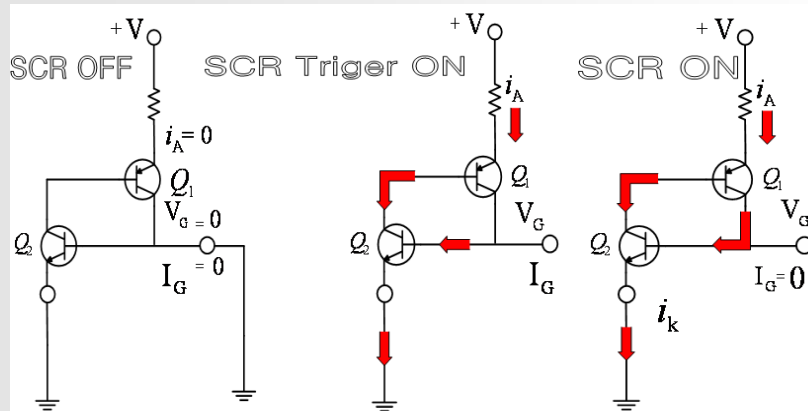
V_{RSM} V	V_{RRM}, V_{DRM} V	$I_{TRMS} = 150$ A (maximum value for continuous operation) $I_{TAV} = 95$ A (sin. 180; $T_c = 85^\circ\text{C}$)		
900	800	SKKT 92/08E	SKKT 92B08E	SKKH 92/08E
1300	1200	SKKT 92/12E	SKKT 92B12E	SKKH 92/12E
1500	1400	SKKT 92/14E	SKKT 92B14E	SKKH 92/14E
1700	1600	SKKT 92/16E	SKKT 92B16E	SKKH 92/16E
1900	1800	SKKT 92/18E	SKKT 92B18E	SKKH 92/18E

Symbol	Conditions	Values	Units
I_{TAV}	sin. 180; $T_c = 85$ (100) $^\circ\text{C}$;	95 (68)	A
I_D	P3/180; $T_a = 45^\circ\text{C}$; B2 / B6	70 / 85	A
I_{RMS}	P3/180F; $T_a = 35^\circ\text{C}$; B2 / B6	140 / 175	A
	P3/180F; $T_a = 35^\circ\text{C}$; W1 / W3	190 / 3 * 135	A
I_{TSM}	$T_{vj} = 25^\circ\text{C}$; 10 ms	2000	A
	$T_{vj} = 125^\circ\text{C}$; 10 ms	1750	A
i_{dt}	$T_{vj} = 25^\circ\text{C}$; 8,3 ... 10 ms	20000	A*s
	$T_{vj} = 125^\circ\text{C}$; 8,3 ... 10 ms	15000	A*s
V_T	$T_{vj} = 25^\circ\text{C}$; $I_T = 300$ A	max. 1,65	V
$V_{T(TD)}$	$T_{vj} = 125^\circ\text{C}$	max. 0,9	V
r_T	$T_{vj} = 125^\circ\text{C}$	max. 2	m Ω
I_{DD}, I_{RD}	$T_{vj} = 125^\circ\text{C}$; $V_{RD} = V_{RRM}$; $V_{DD} = V_{DRM}$	max. 20	mA
t_{gd}	$T_{vj} = 25^\circ\text{C}$; $I_G = 1$ A; $di_G/dt = 1$ A/ μs	1	μs
t_{gr}	$V_D = 0,67 * V_{DRM}$	2	μs
$(di/dt)_{cr}$	$T_{vj} = 125^\circ\text{C}$	max. 150	A/ μs
$(dv/dt)_{cr}$	$T_{vj} = 125^\circ\text{C}$	max. 1000	V/ μs
t_q	$T_{vj} = 125^\circ\text{C}$	100	μs
I_H	$T_{vj} = 25^\circ\text{C}$; typ. / max.	150 / 250	mA
I_L	$T_{vj} = 25^\circ\text{C}$; $R_\theta = 33^\circ\text{C/W}$; typ. / max.	300 / 600	mA
V_{GT}	$T_{vj} = 25^\circ\text{C}$; d.c.	min. 3	V
I_{GT}	$T_{vj} = 25^\circ\text{C}$; d.c.	min. 150	mA
V_{GD}	$T_{vj} = 125^\circ\text{C}$; d.c.	max. 0,25	V
I_{GD}	$T_{vj} = 125^\circ\text{C}$; d.c.	max. 6	mA
$R_{th(G-O)}$	cont.; per thyristor / per module	0,28 / 0,14	KW
$R_{th(G-O)}$	sin. 180; per thyristor / per module	0,3 / 0,15	KW
$R_{th(G-O)}$	rec. 120; per thyristor / per module	0,32 / 0,16	KW
$R_{th(G-S)}$	per thyristor / per module	0,2 / 0,1	KW
T_{vj}		- 40 ... + 125	$^\circ\text{C}$
T_{stg}		- 40 ... + 125	$^\circ\text{C}$



Thyristor (II)

❖ 특성



- Turn-on 조건 : $V_{AK} > 0$ & $i_G > 0$
- Turn-off 조건 : $V_{AK} < 0$

❖ 종류

- SCR (Silicon Controlled Rectifier)
 - Thyristor
 - GTO (Gate Turn Off Thyristor)
 - TRAIC...

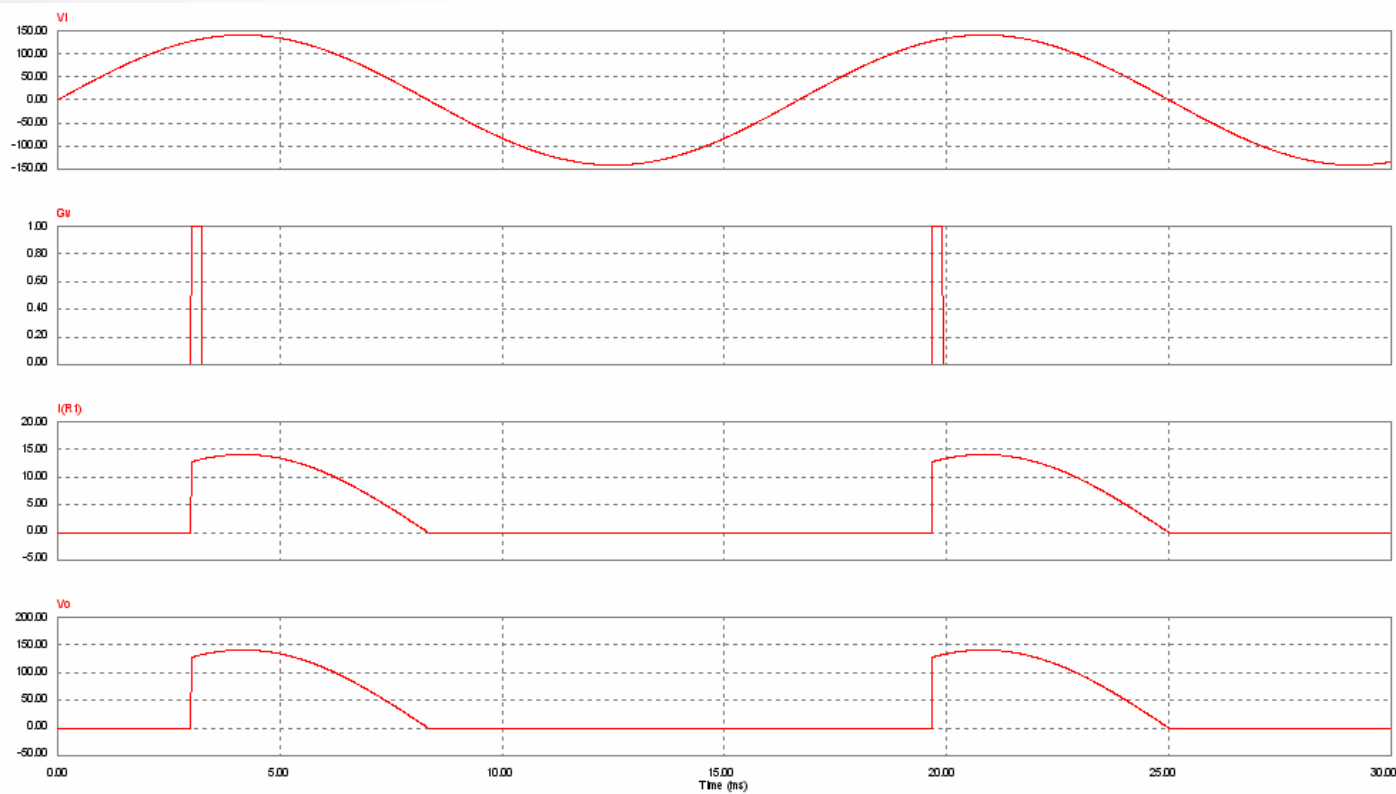
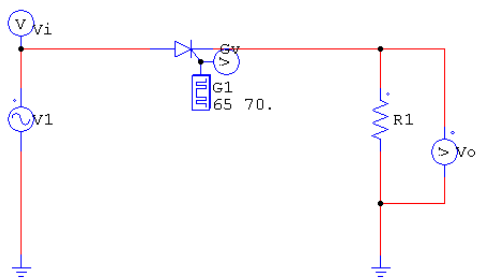
❖ 응용분야

- Controlled rectifier
- AC/DC Motor drive
- Phase control...



Thyristor (III)

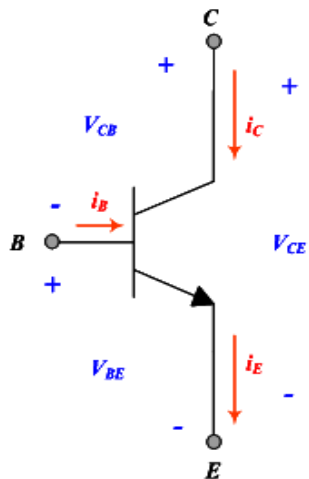
❖ PSIM 시뮬레이션





Power BJT (I)

❖ 심볼



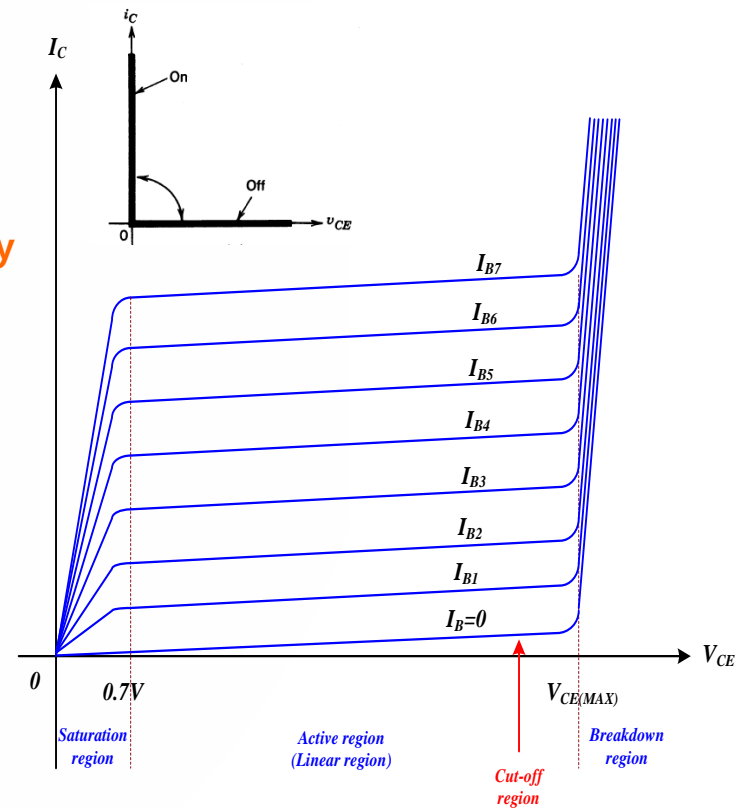
- Current controlled device
- Low switching freq. capability
- High voltage and current capability

$$\text{KCL : } i_E = i_B + i_C$$

$$\text{KVL : } V_{CE} = V_{CB} + V_{BE}$$

- Used commonly in the past
- Now used in specific applications
- Replaced by MOSFETs and IGBTs

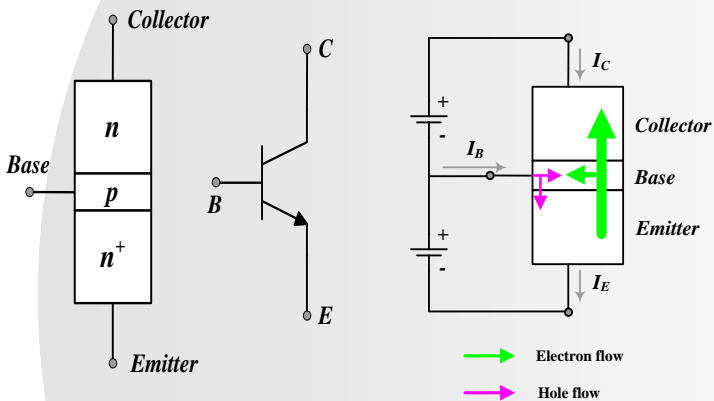
❖ 특성곡선



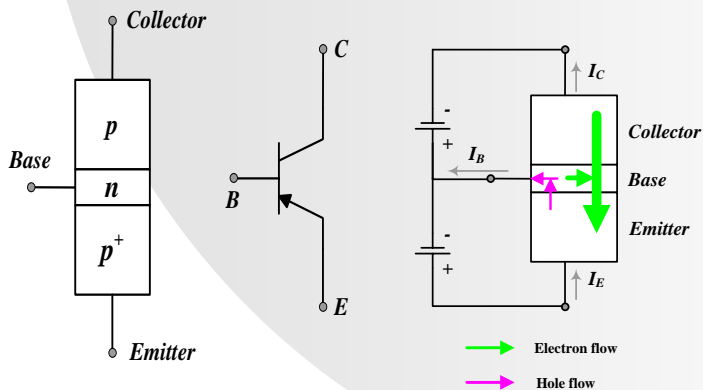


Power BJT (II)

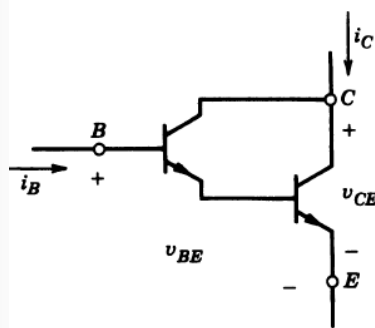
❖ 특성 및 종류



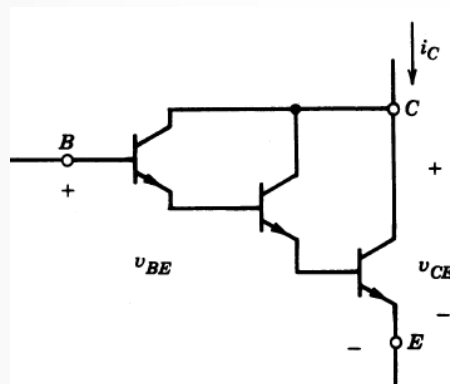
NPN-transistor



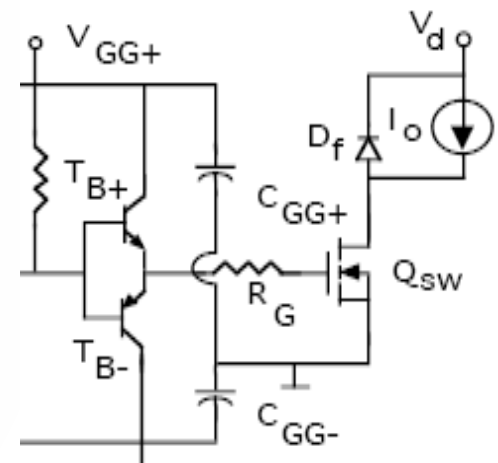
PNP-transistor



Darlington configuration



Triple Darlington configuration

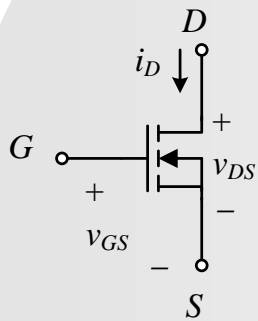


Totem-pole circuit



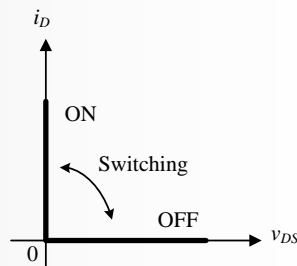
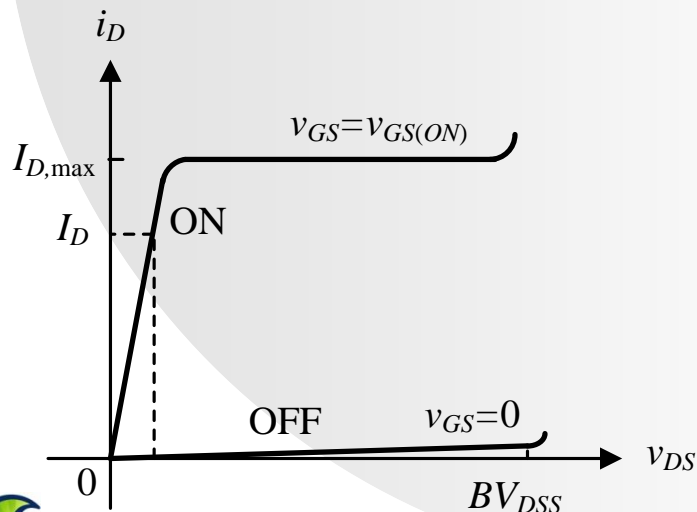
MOSFET (I)

❖ 심볼



- Voltage controlled device
- High switching freq. capability
- Low V_{DS} volt. and curr. capab.
- Very high impedance between gate and source
- $R_{DS(on)}$
- Eq. circuit : Resistor

❖ 특성곡선



❖ Datasheet (example)

IXYS

HiPerFET™ Power MOSFETs

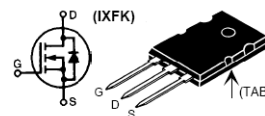
N-Channel Enhancement Mode
Avalanche Rated, High dv/dt, Low t_{rr}

	V_{DSS}	I_{D25}	$R_{DS(on)}$
IXFK 90 N 20	200 V	90 A	23 mΩ
IXFN 100 N 20	200 V	100 A	23 mΩ
IXFN 106 N 20	200 V	106 A	20 mΩ

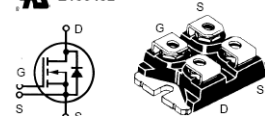
$t_{rr} \leq 200$ ns

Symbol	Test Conditions	Maximum Ratings		
		IXFK	IXFN	IXFN
V_{DSS}	$T_J = 25^\circ\text{C}$ to 150°C	90N20 200	100N20 200	106N20 200 V
V_{DSR}	$T_J = 25^\circ\text{C}$ to 150°C ; $R_{GS} = 1$ MΩ	200	200	200 V
V_{GS}	Continuous	± 20	± 20	20 V
V_{GSM}	Transient	± 30	± 30	20 V
I_{D25}	$T_C = 25^\circ\text{C}$, Chip capability	90 ①	100	106 A
I_{D80}	$T_C = 80^\circ\text{C}$, limited by external leads	76	-	A
I_{DM}	$T_C = 25^\circ\text{C}$, pulse width limited by T_{JM}	360	400	424 A
I_{AR}	$T_C = 25^\circ\text{C}$	50	50	A
E_{AR}	$T_C = 25^\circ\text{C}$	30	30	30 mJ
dv/dt	$I_G \leq I_{GM}$, $di/dt \leq 100$ A/μs, $V_{DS} \leq V_{DSS}$, $T_J \leq 150^\circ\text{C}$, $R_G = 2$ Ω	5	5	5 V/ns
P_D	$T_C = 25^\circ\text{C}$	500	520	W

TO-264 AA



miniBLOC, SOT-227 B (IXFN)
E153432



G = Gate
S = Source
D = Drain
TAB = Drain

Either Source terminal at miniBLOC can be used

Symbol	Test Conditions	Characteristic Values ($T_J = 25^\circ\text{C}$, unless otherwise specified)		
		min.	typ.	max.
V_{DSS}	$V_{GS} = 0$ V, $I_D = 1$ mA	200		V
$V_{GH(th)}$	$V_{DS} = V_{GS}$, $I_D = 8$ mA	2		4 V
I_{GSS}	$V_{GS} = \pm 20$ V, $V_{DS} = 0$			± 200 nA
I_{DSS}	$V_{DS} = 0.8 \cdot V_{DSS}$, $V_{GS} = 0$ V			400 μA 2 mA
$R_{DS(on)}$	$V_{GS} = 10$ V, $I_D = 0.5 \cdot I_{D25}$ Pulse test, $t \leq 300$ μs, duty cycle $d \leq 2$ %			0.023 Ω 0.023 Ω 0.020 Ω
				IXFK90N20 IXFN100N20 IXFN106N20



MOSFET (II)

❖ Datasheet (example)

Symbol	Test Conditions	Characteristic Values ($T_J = 25^\circ\text{C}$, unless otherwise specified)		
		min.	typ.	max.
g_{fs}	$V_{DS} = 10\text{ V}$; $I_D = 0.5 \cdot I_{D25}$, pulse test		60	S
C_{iss}	$V_{GS} = 0\text{ V}$, $V_{DS} = 25\text{ V}$, $f = 1\text{ MHz}$		9000	pF
C_{oss}			1600	pF
C_{rss}			590	pF
$t_{d(on)}$	$V_{GS} = 10\text{ V}$, $V_{DS} = 0.5 \cdot V_{DSS}$, $I_D = 0.5 \cdot I_{D25}$ $R_G = 1\ \Omega$ (External),		30	ns
t_r			80	ns
$t_{d(off)}$			75	ns
t_f			30	ns
$Q_{g(on)}$	$V_{GS} = 10\text{ V}$, $V_{DS} = 0.5 \cdot V_{DSS}$, $I_D = 0.5 \cdot I_{D25}$		380	nC
Q_{gs}			70	nC
Q_{gd}			190	nC
R_{thJC}	TO-264 AA		0.25	K/W
R_{thCK}	TO-264 AA		0.15	K/W
R_{thJC}	miniBLOC, SOT-227 B		0.24	K/W
R_{thCK}	miniBLOC, SOT-227 B		0.05	K/W

Source-Drain Diode		Characteristic Values ($T_J = 25^\circ\text{C}$, unless otherwise specified)		
Symbol	Test Conditions	min.	typ.	max.
I_S	$V_{GS} = 0\text{ V}$			90 A 100 A 106 A
I_{SM}	Repetitive; pulse width limited by T_{JM}			360 A 424 A
V_{SD}	$I_F = 100\text{ A}$, $V_{GS} = 0\text{ V}$, Pulse test, $t \leq 300\ \mu\text{s}$, duty cycle $d \leq 2\%$			1.5 V
t_{rr}	$I_F = 50\text{ A}$, $-di/dt = 100\text{ A}/\mu\text{s}$, $V_R = 100\text{ V}$		3	ns
Q_{RM}			38	μC
I_{RM}				A

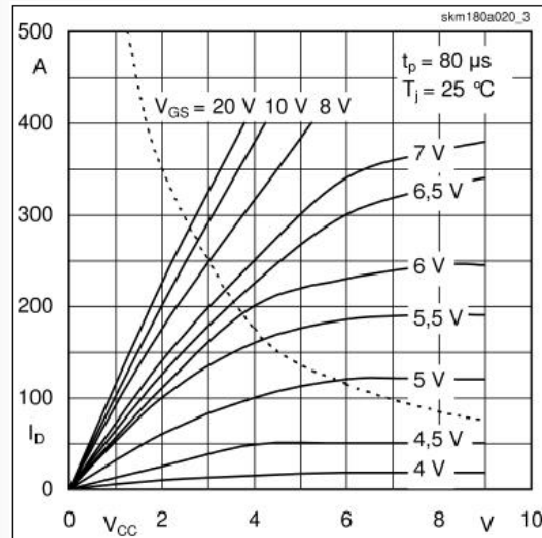


Fig. 3 Output characteristic

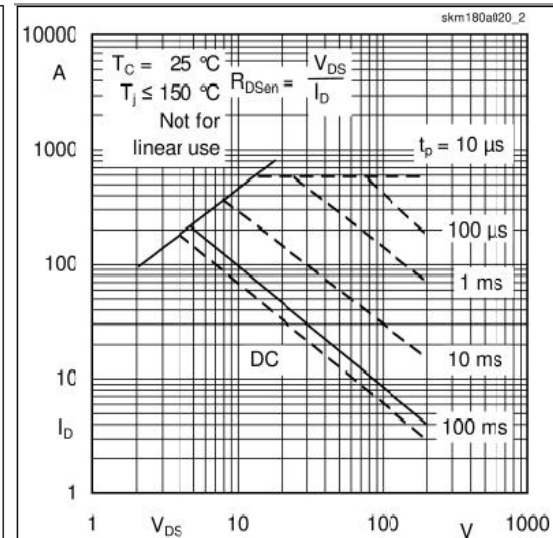


Fig. 2 Maximum safe operating area

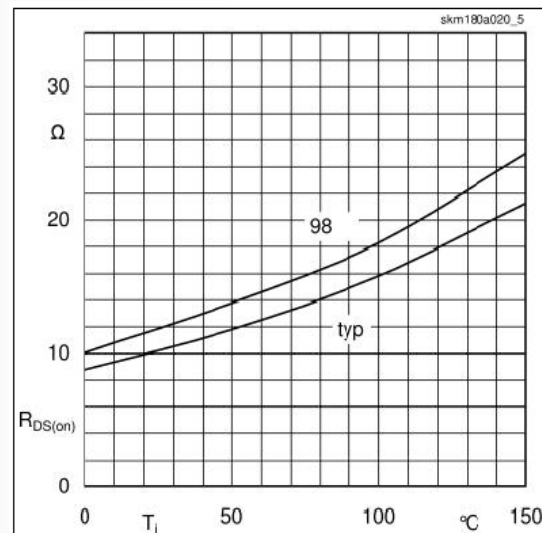


Fig. 5 On-resistance vs. temperature

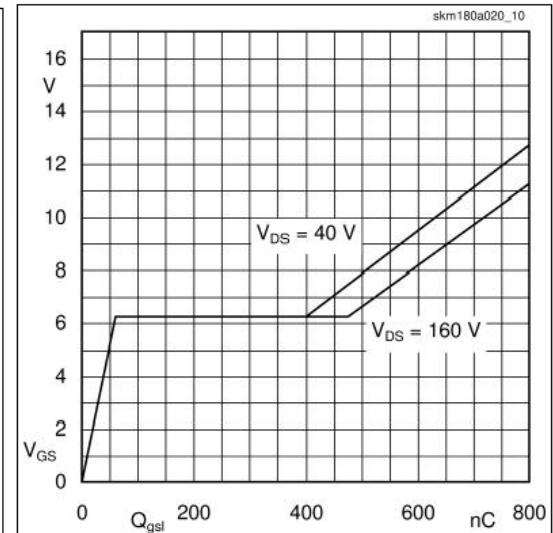
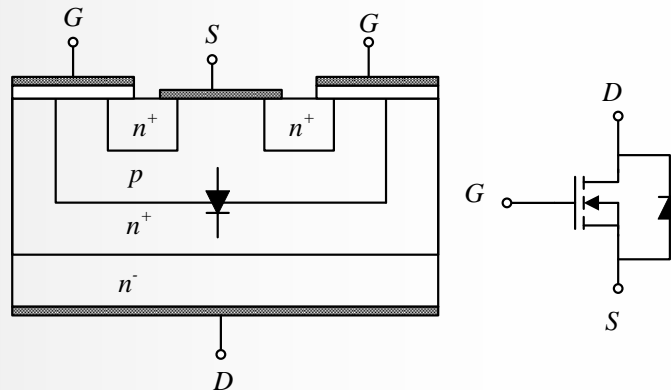


Fig. 10 Gate charge characteristic



MOSFET (III)

❖ 특성



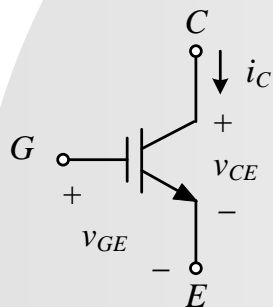
- 제조과정상 역병렬 다이오드 생성됨
- Body diode는 역회복시간이 수백ns~수us 정도로 비교적 느림
- 일반적으로 외부에 Shottky diode 달아줌
- MOSFET의 온 저항(on-resistance)은 최대 차단전압 BV_{DSS} 가 클 수록 증가함

$$r_{DS(ON)} \propto BV_{DSS}^{2.5 \sim 2.7}$$



IGBT (I)

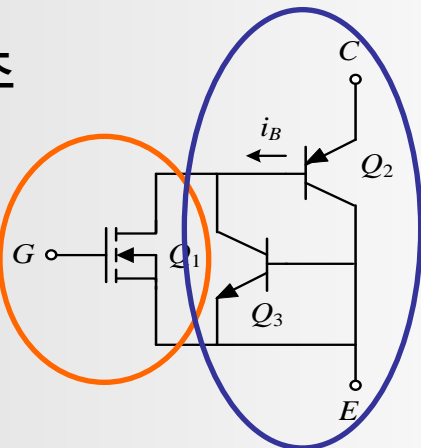
❖ 심볼



- Voltage controlled device
- Mid. switching freq. capability
- Mid. V_{DS} volt. and curr. capab.
- Very high impedance between gate and source
- $V_{CE(sat)}$
- Eq. circuit : Voltage source

❖ 내부구조

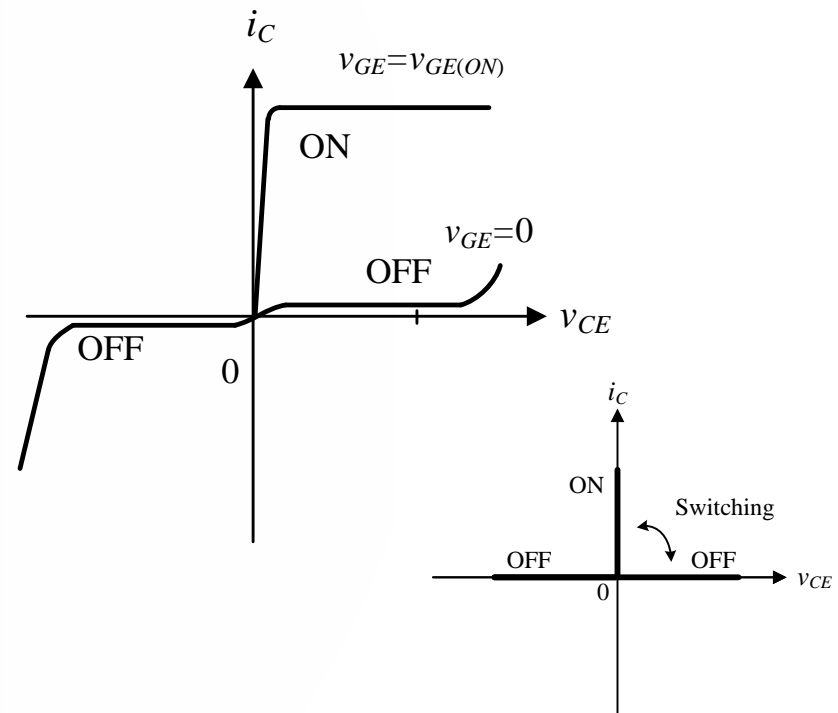
- MOSFET
→ 속도빠름



- Transistor
→ 내압 높음

- IGBT (Insulated Gate Bipolar Transistor)
- Transistor와 MOSFET의 장점만 조합하여 만듦

❖ 특성곡선



- BJT와 같이 On-drop이 전류에 관계없이 낮고 일정
- GTO와 같이 역방향 전압 저지 특성 가짐



IGBT (II)

❖ Datasheet (example)

Absolute Maximum Ratings		$T_c = 25\text{ }^{\circ}\text{C}$, unless otherwise specified		
Symbol	Conditions	Values	Units	
IGBT				
V_{CES}	$T_j = 25\text{ }^{\circ}\text{C}$	1200	V	
I_C	$T_j = 150\text{ }^{\circ}\text{C}$	$T_{case} = 25\text{ }^{\circ}\text{C}$	200	A
		$T_{case} = 85\text{ }^{\circ}\text{C}$	180	A
I_{CRM}	$I_{CRM}=2 \times I_{Cnom}$	300	A	
V_{GES}		± 20	V	
t_{psc}	$V_{CC} = 600\text{ V}; V_{GE} \leq 20\text{ V}; V_{CES} < 1200\text{ V}$	$T_j = 125\text{ }^{\circ}\text{C}$	10	μs
Inverse Diode				
I_F	$T_j = 150\text{ }^{\circ}\text{C}$	$T_{case} = 25\text{ }^{\circ}\text{C}$	200	A
		$T_{case} = 80\text{ }^{\circ}\text{C}$	130	A
I_{FRM}	$I_{FRM}=2 \times I_{Fnom}$	300	A	
I_{FSM}	$t_p = 10\text{ ms}; \sin.$	$T_j = 150\text{ }^{\circ}\text{C}$	1440	A
Freewheeling Diode				
I_F	$T_j = 150\text{ }^{\circ}\text{C}$	$T_{case} = 25\text{ }^{\circ}\text{C}$	260	A
		$T_{case} = 80\text{ }^{\circ}\text{C}$	180	A
I_{FRM}	$I_{FRM}=2 \times I_{Fnom}$	400	A	
I_{FSM}	$t_p = 10\text{ ms}; \sin.$	$T_j = 150\text{ }^{\circ}\text{C}$	1800	A
Module				
$I_{T(RMS)}$		500	A	
T_{vj}		- 40 ... + 150 (125)	$^{\circ}\text{C}$	
T_{stg}		- 40...+ 125	$^{\circ}\text{C}$	
V_{isol}	AC, 1 min.	2500	V	

Characteristics					
Symbol	Conditions	min.	typ.	max.	Units
Inverse Diode					
$V_F = V_{EC}$	$I_{Fnom} = 150\text{ A}; V_{GE} = 0\text{ V}$	$T_j = 25^\circ\text{C}_{chiplev.}$	2	2,5	V
		$T_j = 125^\circ\text{C}_{chiplev.}$	1,8		V
V_{FO}		$T_j = 25^\circ\text{C}$	1,1	1,2	V
		$T_j = 125^\circ\text{C}$			V
r_F		$T_j = 25^\circ\text{C}$	6	8,7	m Ω
		$T_j = 125^\circ\text{C}$			m Ω
I_{RRM}	$I_{Fnom} = 150\text{ A}$	$T_j = 125^\circ\text{C}$	90		A
Q_{rr}	$di/dt = 1500\text{ A}/\mu\text{s}$		8		μC
E_{rr}	$V_{GE} = -15\text{ V}; V_{CC} = 600\text{ V}$		6,6		mJ
$R_{th(j-c)D}$	per diode		0,25		K/W
Freewheeling Diode					
$V_F = V_{EC}$	$I_{Fnom} = 200\text{ A}; V_{GE} = 0\text{ V}$	$T_j = 25^\circ\text{C}_{chiplev.}$	2	2,5	V
		$T_j = 125^\circ\text{C}_{chiplev.}$	1,8		V
V_{FO}		$T_j = 25^\circ\text{C}$	1,1	1,2	V
		$T_j = 125^\circ\text{C}$			V
r_F		$T_j = 25^\circ\text{C}$	4,5	6,5	V
		$T_j = 125^\circ\text{C}$			V
I_{RRM}	$I_{Fnom} = 200\text{ A}$	$T_j = 125^\circ\text{C}$	120		A
Q_{rr}	$di/dt = 2000\text{ A}/\mu\text{s}$		11		μC
E_{rr}	$V_{GE} = 0\text{ V}; V_{CC} = 600\text{ V}$				mJ
$R_{th(j-c)FD}$	per diode		0,18		K/W
Module					
L_{CE}			15	20	nH
$R_{CC+EE'}$	res., terminal-chip	$T_{case} = 25^\circ\text{C}$	0,35		m Ω
		$T_{case} = 125^\circ\text{C}$	0,5		m Ω
$R_{th(o-s)}$	per module		0,038		K/W
M_s	to heat sink M6		3	5	Nm
M_t	to terminals M6, M4		2,5	5	Nm
W			325		g

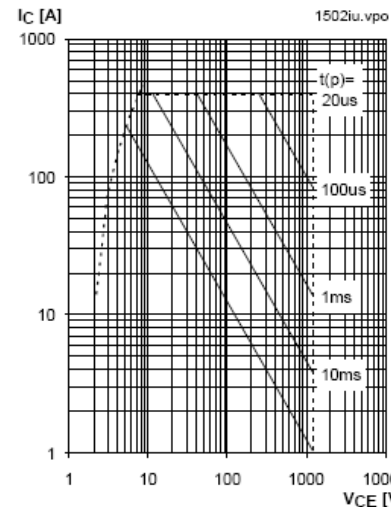


IGBT (III)

❖ Datasheet

Absolute Maximum Ratings		T _c = 25 °C, unless otherwise specified		
Symbol	Conditions	Values	Units	
IGBT				
V _{CES}	T _j = 25 °C	1200	V	
I _C	T _j = 150 °C	T _{case} = 25 °C	200	A
		T _{case} = 85 °C	180	A
I _{CRM}	I _{CRM} = 2xI _{Cnom}	300	A	
V _{GES}		± 20	V	
t _{pso}	V _{CC} = 600 V; V _{GE} ≤ 20 V; V _{CES} < 1200 V	T _j = 125 °C	10	µs
Inverse Diode				
I _F	T _j = 150 °C	T _{case} = 25 °C	200	A
		T _{case} = 80 °C	130	A
I _{FRM}	I _{FRM} = 2xI _{Fnom}	300	A	
I _{FSM}	t _p = 10 ms; sin.	T _j = 150 °C	1440	A
Freewheeling Diode				
I _F	T _j = 150 °C	T _{case} = 25 °C	260	A
		T _{case} = 80 °C	180	A
I _{FRM}	I _{FRM} = 2xI _{Fnom}	400	A	
I _{FSM}	t _p = 10 ms; sin.	T _j = 150 °C	1800	A
Module				
I _{k(RMS)}		500	A	
T _{vj}		- 40 ... + 150 (125)	°C	
T _{stg}		- 40...+ 125	°C	
V _{isol}	AC, 1 min.	2500	V	
Module				
L _{CE}		15 20	nH	
R _{CC+EE'}	res., terminal-chip	T _{case} = 25 °C	0,35	mΩ
		T _{case} = 125 °C	0,5	mΩ
R _{th(o-s)}	per module	0,038	K/W	
M _s	to heat sink M6	3 5	Nm	
M _t	to terminals M6, M4	2,5 5	Nm	
w		325	g	

• 안전동작영역 (SOA)



1 pulse
 $T_C = 25^\circ\text{C}$
 $T_j \leq 150^\circ\text{C}$

Not for
 linear use

Fig. 4 Maximum safe operating area (SOA) $I_C = f(V_{CE})$

• 역바이어스 안전동작영역 (RBSOA)

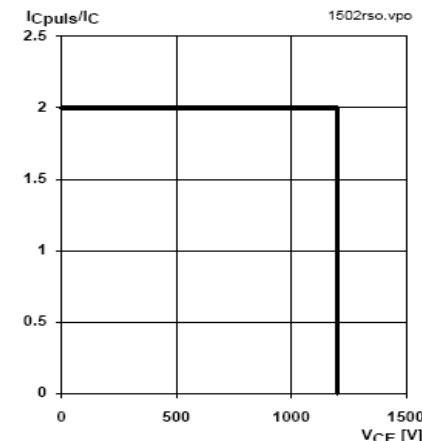
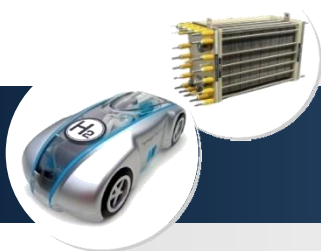


Fig. 5 Turn-off safe operating area (RBSOA)

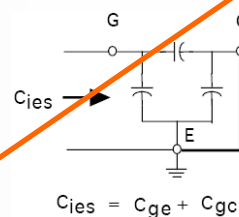
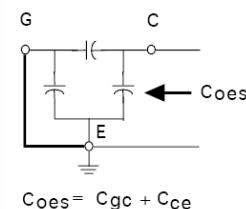
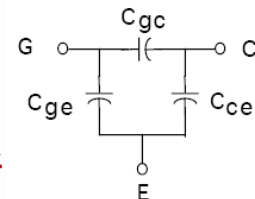


IGBT (IV)

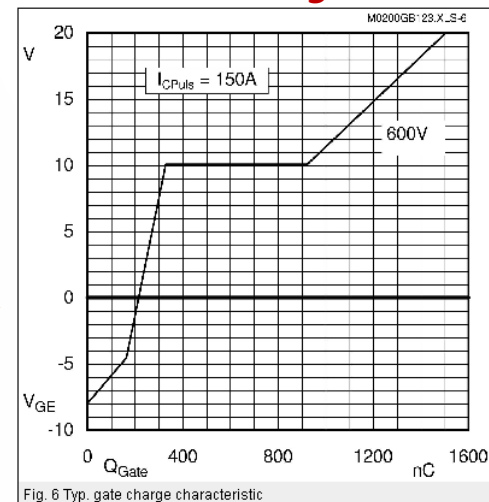
❖ Datasheet

• IGBT 내부 커패시턴스

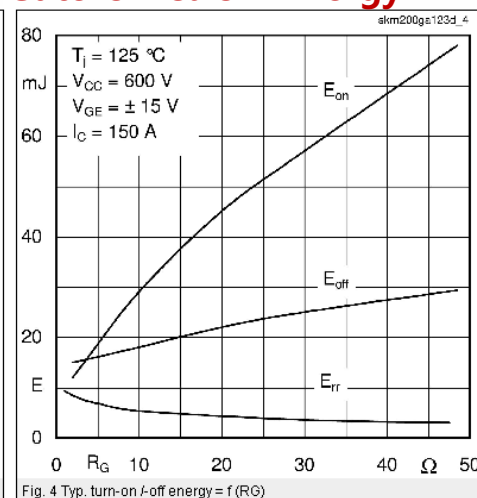
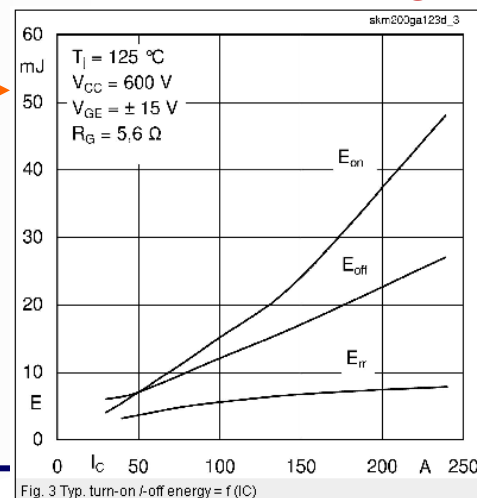
Characteristics		$T_c = 25^\circ\text{C}$, unless otherwise specified			
Symbol	Conditions	min.	typ.	max.	Units
IGBT					
$V_{GE(th)}$	$V_{GE} = V_{CE}, I_C = 6\text{ mA}$	4,5	5,5	6,5	V
I_{CES}	$V_{GE} = 0\text{ V}, V_{CE} = V_{CES}$		0,1	0,3	mA
V_{CE0}			$T_j = 25^\circ\text{C}$	1,4	V
			$T_j = 125^\circ\text{C}$	1,6	V
r_{CE}	$V_{GE} = 15\text{ V}$		$T_j = 25^\circ\text{C}$	7,33	m Ω
			$T_j = 125^\circ\text{C}$	10	m Ω
$V_{CE(sat)}$	$I_{Cnom} = 150\text{ A}, V_{GE} = 15\text{ V}$		$T_j = ^\circ\text{C}_{chiplev.}$	2,5	V
C_{ies}	$V_{CE} = 25\text{ V}, V_{GE} = 0\text{ V}$			10	nF
C_{oes}			$f = 1\text{ MHz}$	1,5	nF
C_{res}				0,8	nF
Q_G	$V_{GE} = -8\text{ V} - +20\text{ V}$			1500	nC
R_{Gint}	$T_j = ^\circ\text{C}$			2,5	Ω
$t_{d(on)}$	$R_{Gon} = 5,6\ \Omega$		$V_{CC} = 600\text{ V}$	220	ns
t_r				100	ns
E_{on}	$R_{Goff} = 5,6\ \Omega$		$I_{Cnom} = 150\text{ A}$	24	mJ
$t_{d(off)}$				600	ns
t_f			$T_j = 125^\circ\text{C}$	70	ns
t_{off}				17	ns
$R_{th(j-c)}$	per IGBT			0,09	KW



• IGBT Gate Charge



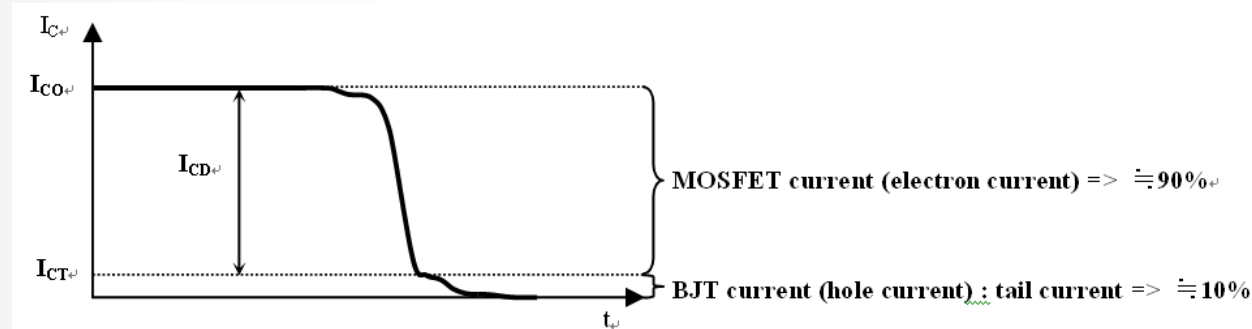
• IGBT Gate On & Off Energy



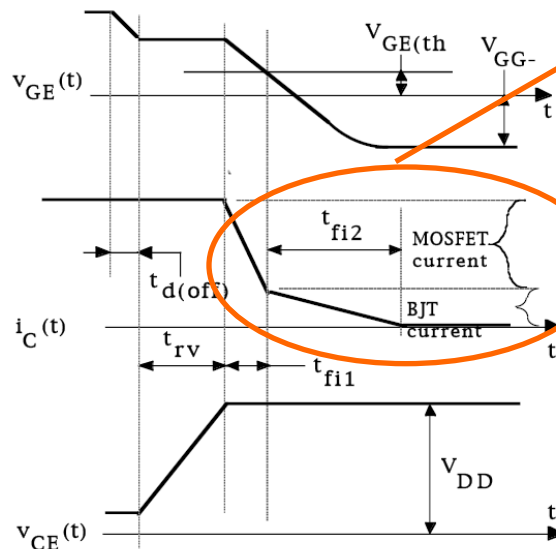


IGBT (V)

❖ Tail current 특성

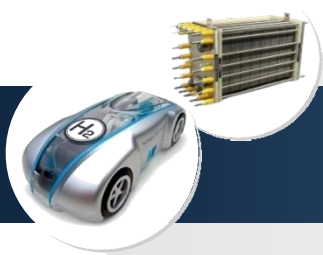


IGBT Turn-off Waveforms



- Turn-off waveforms for IGBT embedded in a stepdown converter.
- Current "tailing" (t_{fi2}) due to stored charge trapped in drift region (base of pnp BJT) by rapid turn-off of MOSFET section.
- Shorten tailing interval by either reducing carrier lifetime or by putting N^+ buffer layer adjacent to injecting P^+ layer at drain.
- Buffer layer acts as a sink for excess holes otherwise trapped in drift region because lifetime in buffer layer can be made small without affecting on-state losses - buffer layer thin compared to drift region.

- IGBT는 MOSFET의 turn-off 특성과 BJT의 turn-off 특성을 모두 가지고 있음
- Tail current 발생
- Switching 특성 감소시키고 loss 증가시킴
- Tail current 영향 줄이기 위해 MOSFET와 달리 Gate turn-off 시 (-) 전압 인가해야 함



Summary (I)

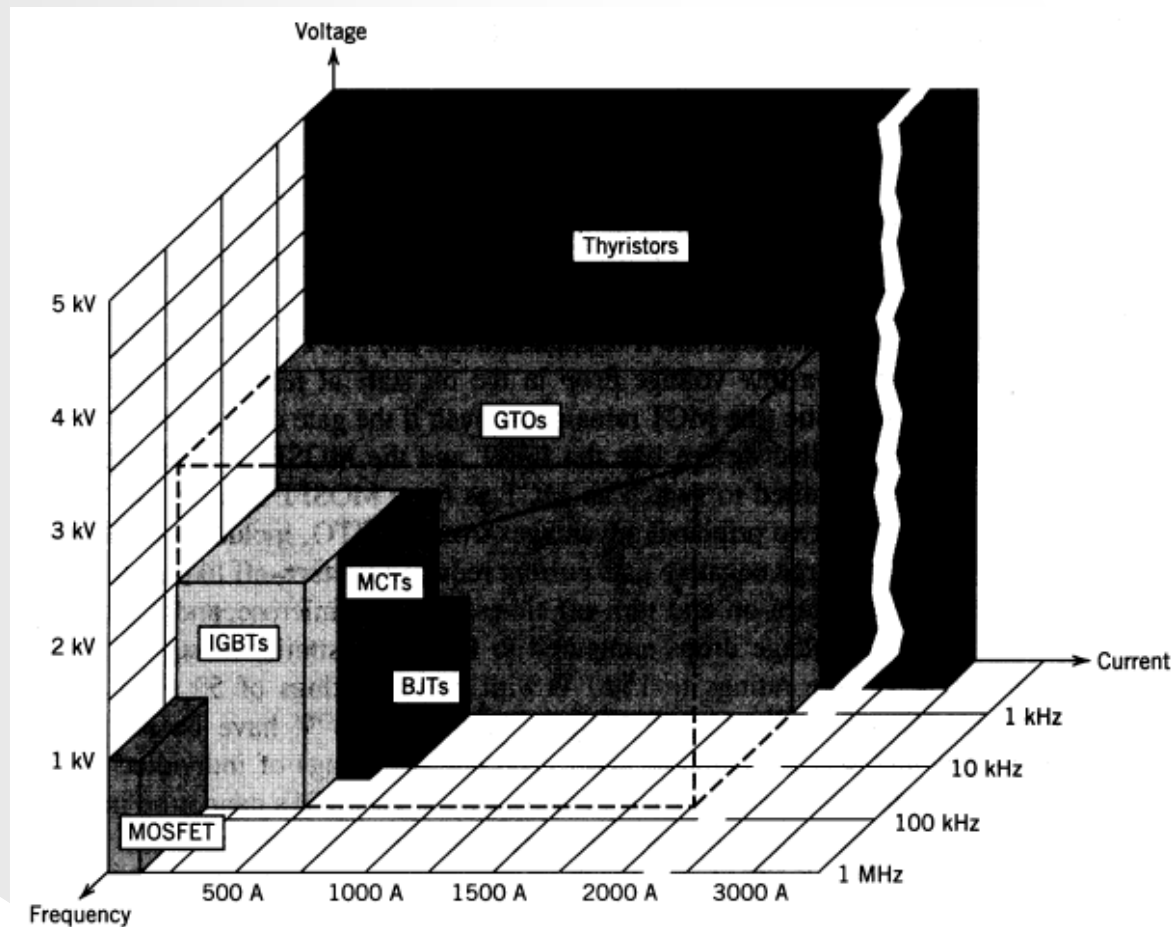
❖ 스위칭 주파수, 게이트 구동방식, 용량 등에 따른 비교

	Diode	Thyristor	Power BJT	MOSFET	IGBT
On & Off control	-	△	△	◎	◎
Voltage capability	◎	◎	◎	△	○
Current capability	◎	◎	◎	△	○
Switching frequency	-	△	△	◎	○
Gate drive method	-	△	△	◎	◎



Summary (II)

❖ 전압, 전류, 주파수에 따른 상용 전력용 반도체 구성

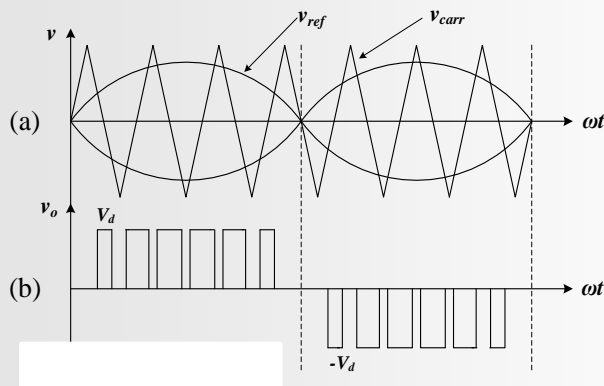




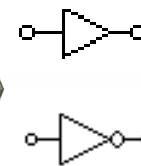
Fundamental (I)

❖ Operational Amplifier

- 연산작용 : 사칙연산 (신호의 크기 증폭)
- 증폭작용 : 신호의 전력 (힘) 증폭



1 & 0



• Buffer



1 & 0

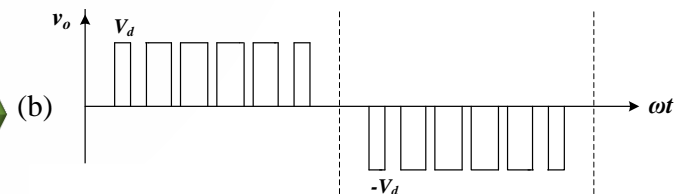
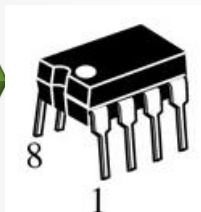
0 & 1

$$1) V_{ref} + V_{carr}$$

$$2) V_{ref} - V_{carr}$$

$$3) V_{ref} \div V_{carr}$$

$$4) V_{ref} \times V_{carr}$$





Fundamental (II)

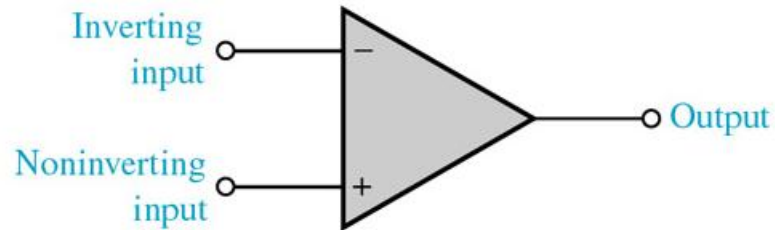
❖ OP-Amp의 역사

- **Operational Amplifier** : 다양한 수학적 연산을 위해서 제작 (1948)
- **Integrated circuit op amps**
 - Fairchild : 702, 709, 741 (1964 ~ 1968)
 - National : 101, 301
- ▶ small size, low cost, short design time
- **Transistor type \Rightarrow FET type**
- ▶ low input current, high input impedance, more fast
- **Dual and quad op amp packages**
- **Application based op amps (Specialization)**

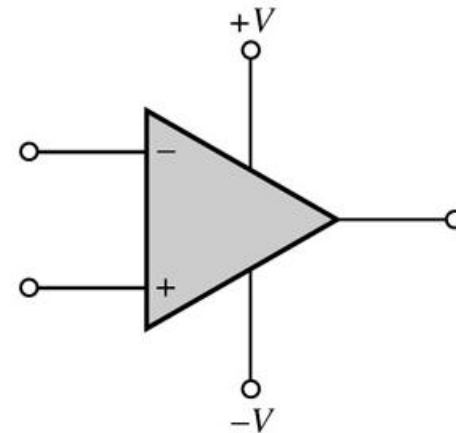


Fundamental (III)

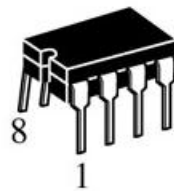
❖ OP-Amp의 구조



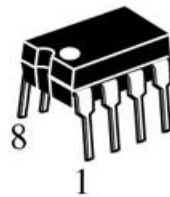
(a) Symbol



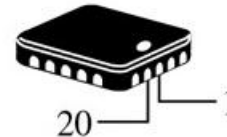
(b) Symbol with dc supply connections



DIP



DIP



SMT



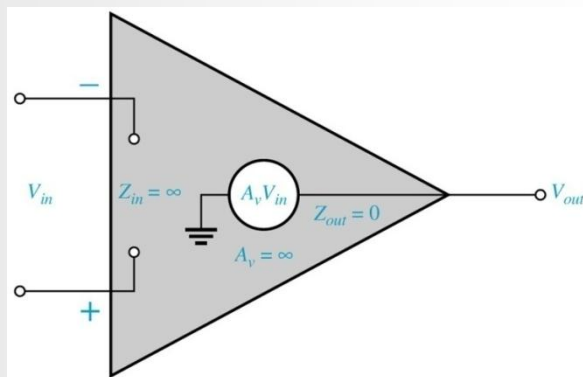
SMT

(c) Typical packages. Pin 1 is indicated by a notch or dot on dual-in-line (DIP) and surface-mount technology (SMT) packages, as shown.



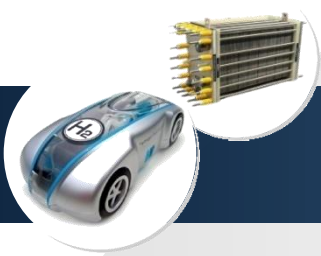
Fundamental (IV)

❖ OP-Amp의 특성



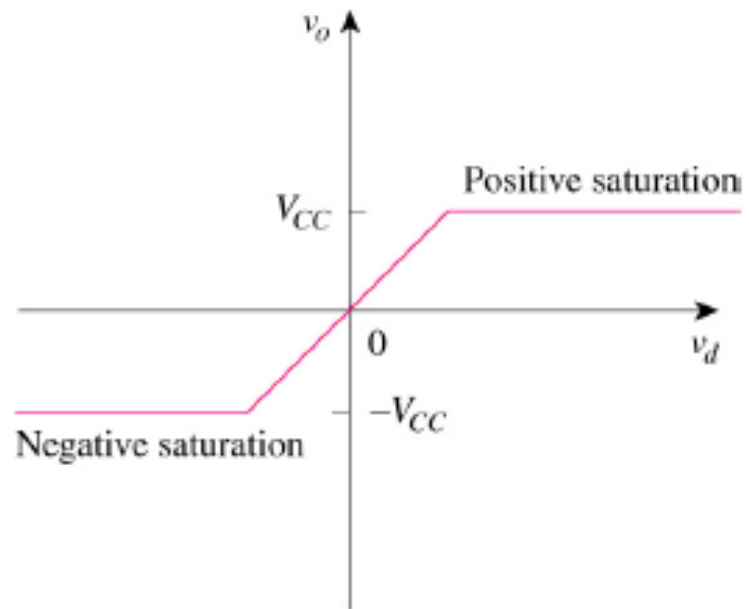
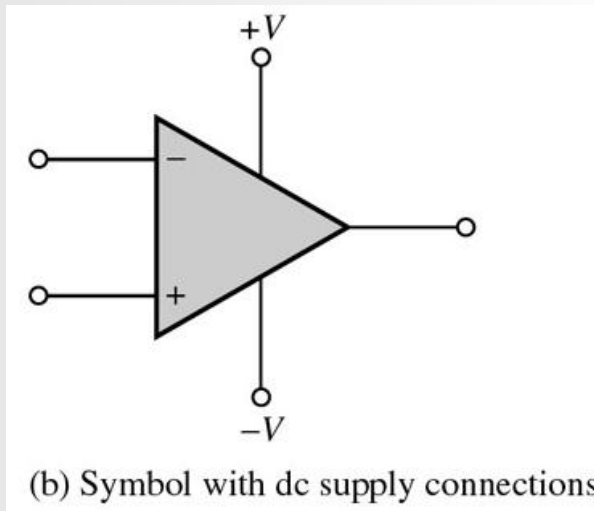
$$V_{out} = A_v (V_{in2} - V_{in1})$$

Ideal	Practical	Remarks	
Infinite Voltage Gain	Very Large Volt. Gain	around 200,000	잘 키우고
Infinite Bandwidth	Very Large Bandwidth	kHz - MHz order	잘 보내주고
Infinite Input Impedance	Very Large Input Z	Very small input current	신호의 왜곡 없게
Zero Output Impedance	Very Small Output Z	Very small IO resistance	신호의 왜곡 없게
Virtually Internal Short	가상단락	두 입력단자의 전위 동일	

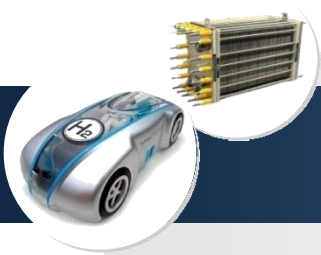


Fundamental (V)

❖ OP-Amp의 특성



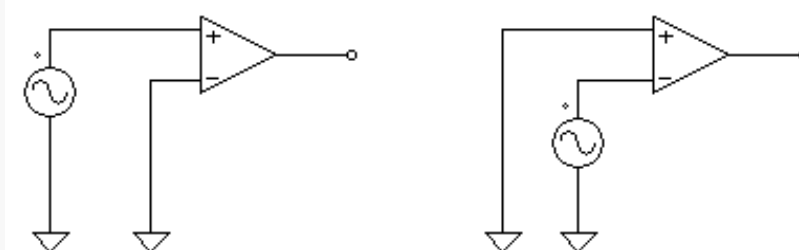
1. Positive saturation, $v_o = V_{CC}$
2. Linear region, $-V_{CC} \leq v_o = Av_d \leq V_{CC}$
3. Negative saturation, $v_o = -V_{CC}$



Fundamental (VI)

❖ OP-Amp의 입력모드

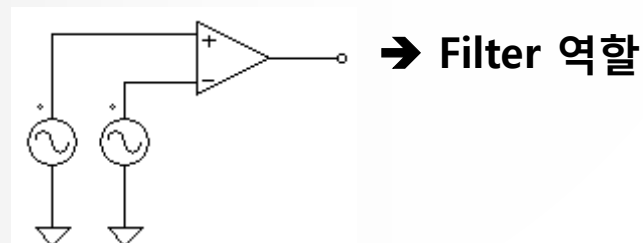
▪ Single-ended mode:



▪ Double-ended mode:



▪ Common mode:





Fundamental (VII)

❖ Slew Rate

- 출력전압이 얼마나 빨리 변하느냐를 표시

$$SR = \frac{\Delta V_o}{\Delta t} \quad [V / \mu s]$$

$$SR = \frac{I}{C} = \frac{15 \mu A}{30 pF} = 0.5 [V / \mu s]$$

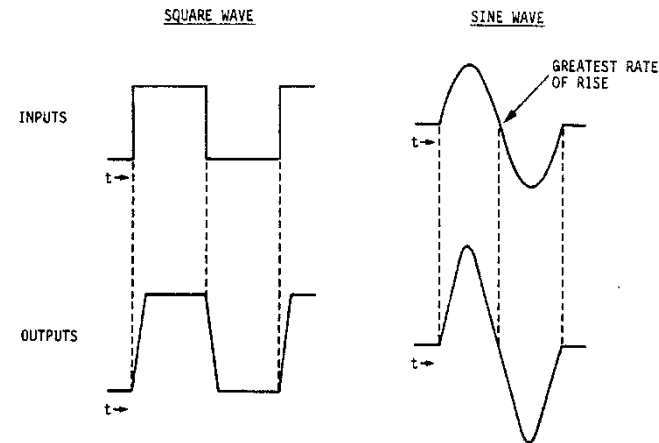
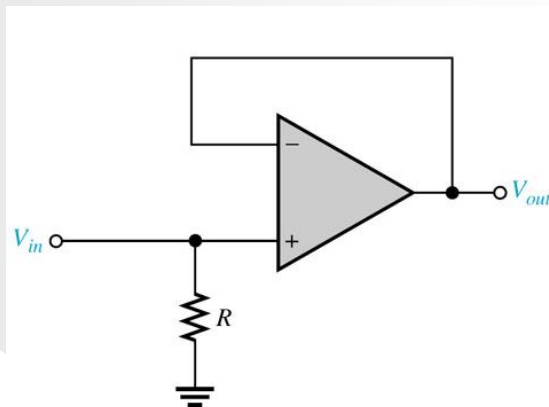
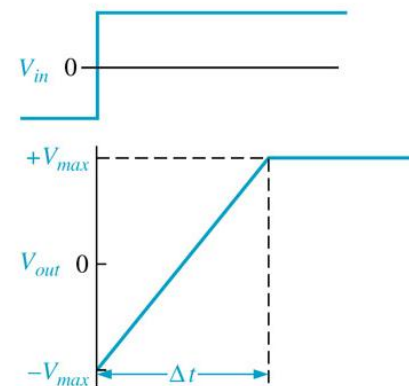


Figure 1-17 Effect of Slew Rate on Output



(a) Test circuit

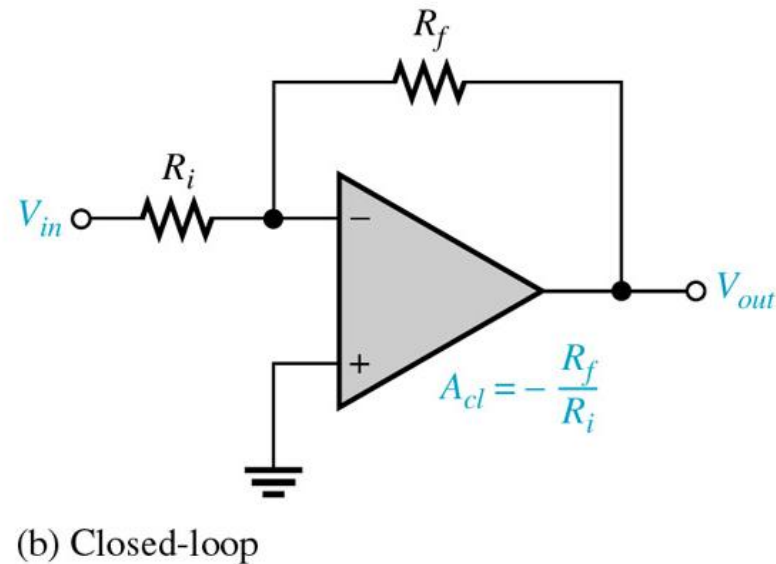
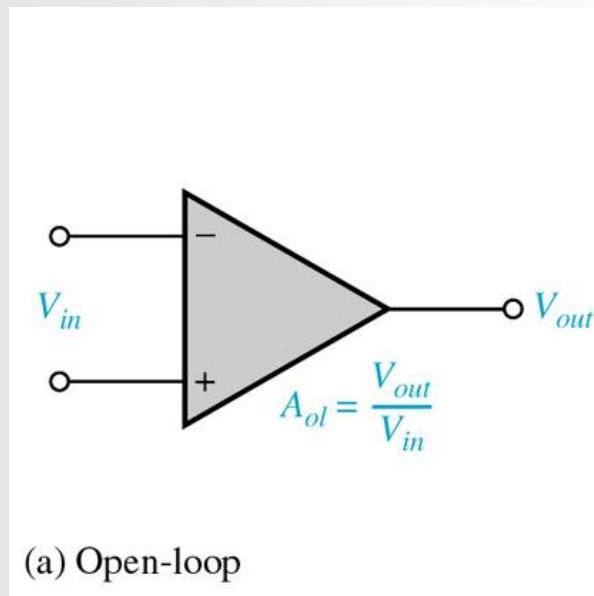


(b) Step input voltage and the resulting output voltage



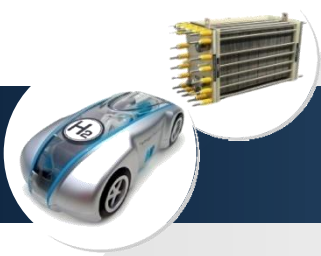
Fundamental (VIII)

❖ Open Loop & Closed Loop



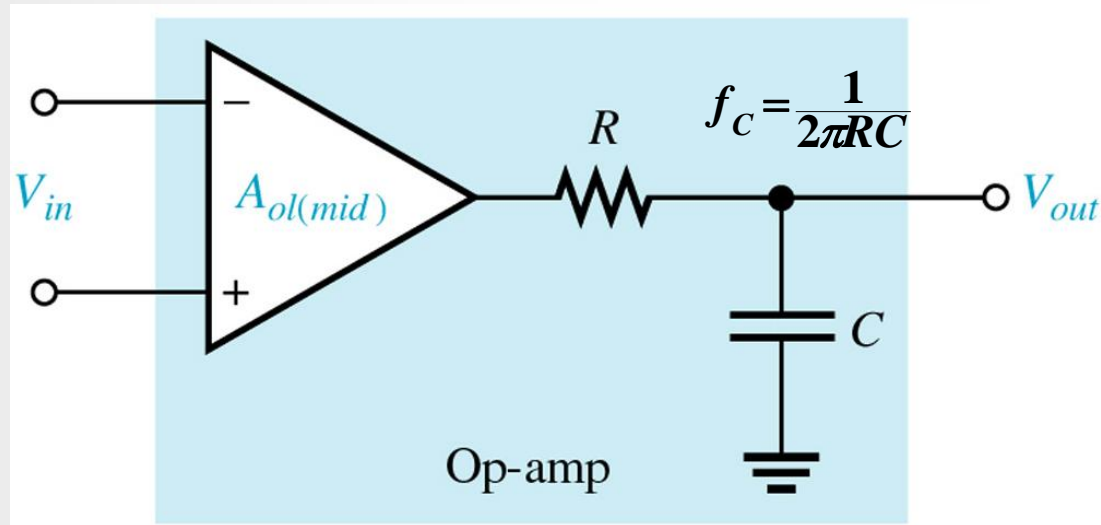
▪ 입력과 출력이 연결되지 않음

▪ 출력신호가 입력으로 궤환됨



Fundamental (IX)

❖ OP-Amp의 등가회로



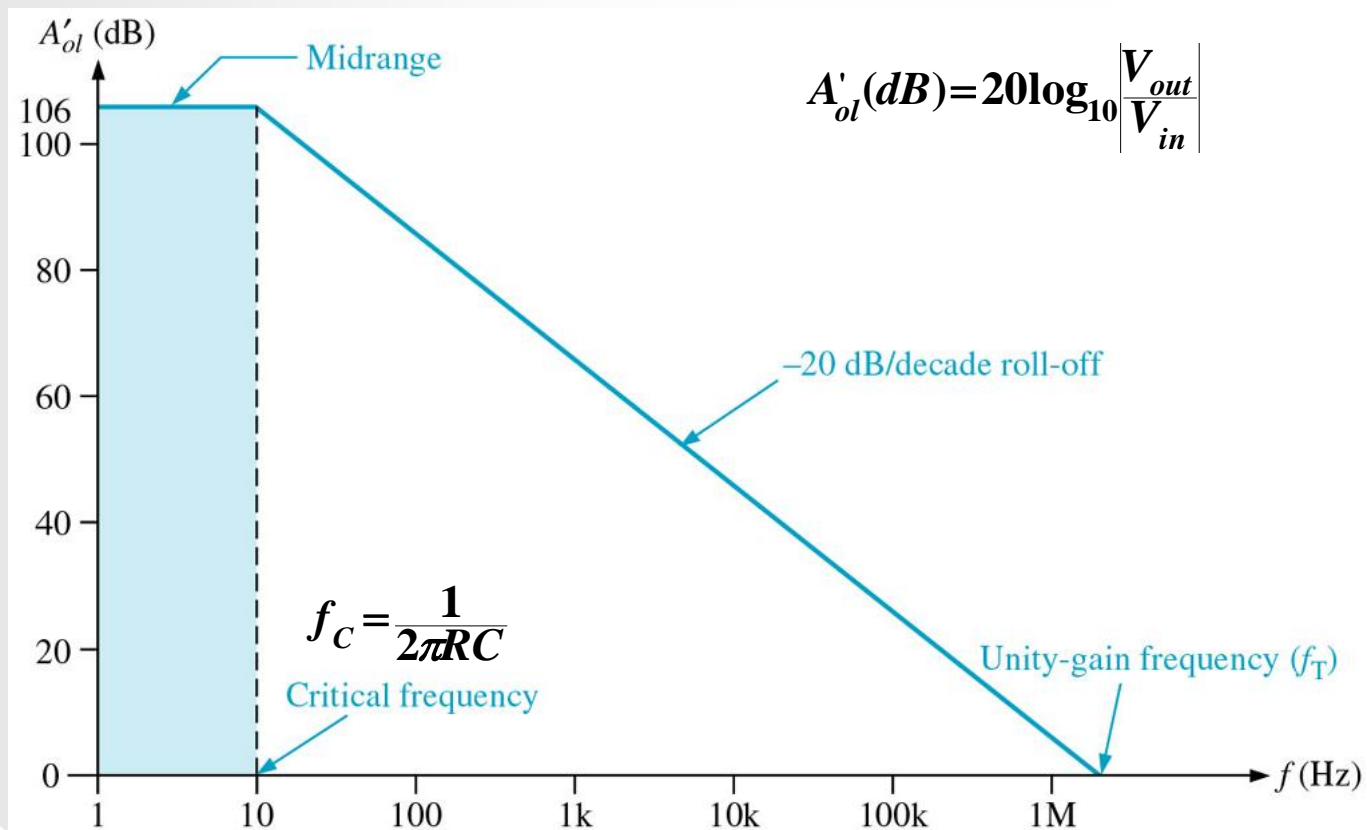
Total Gain :

$$\frac{V_{out}}{V_{in}} = A_{ol} \cdot \frac{1}{RCs + 1}$$



Fundamental (X)

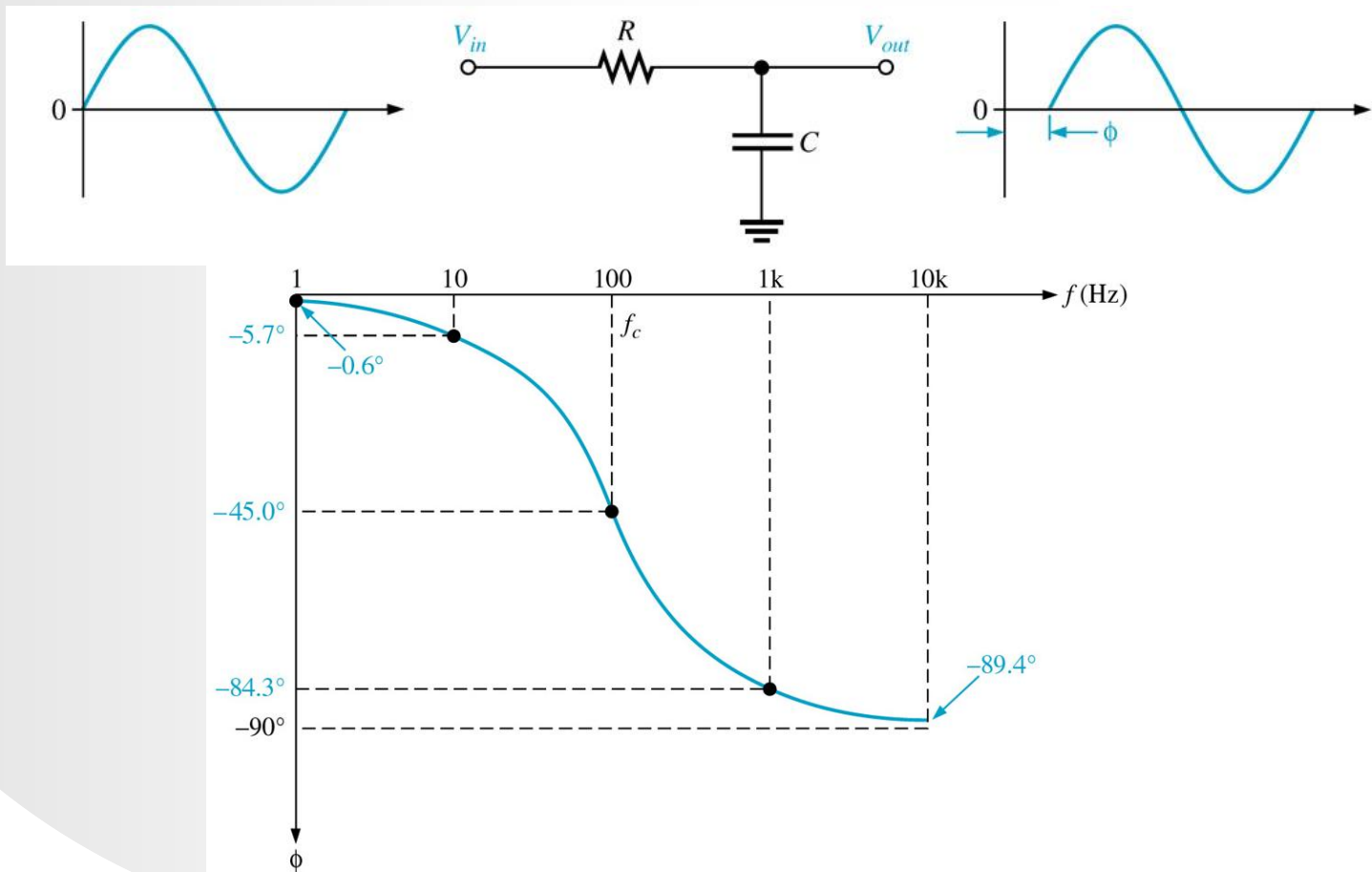
❖ Open-Loop의 주파수 특성





Fundamental (XI)

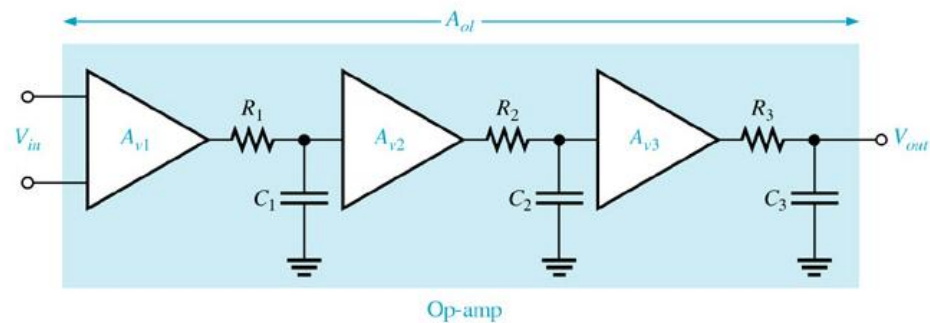
❖ Phase delay between Input & Output



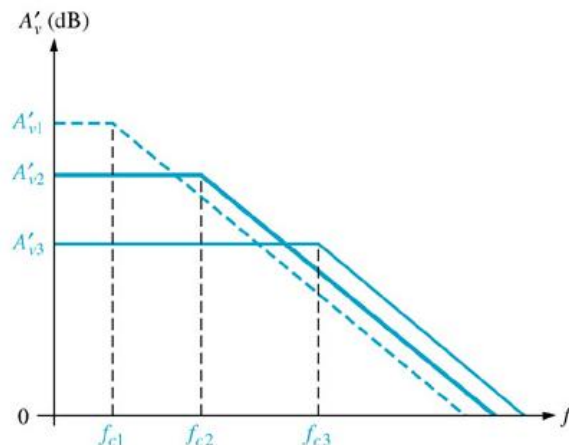


Fundamental (XII)

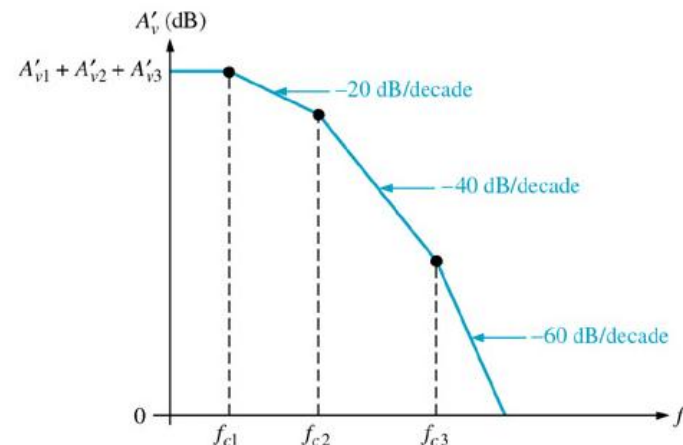
❖ Multi-Stages의 주파수 특성



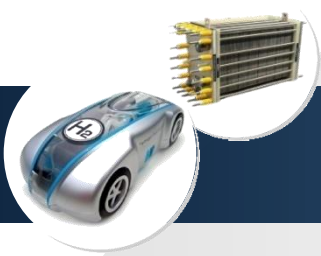
(a) Representation of an op-amp with three internal stages



(b) Individual responses

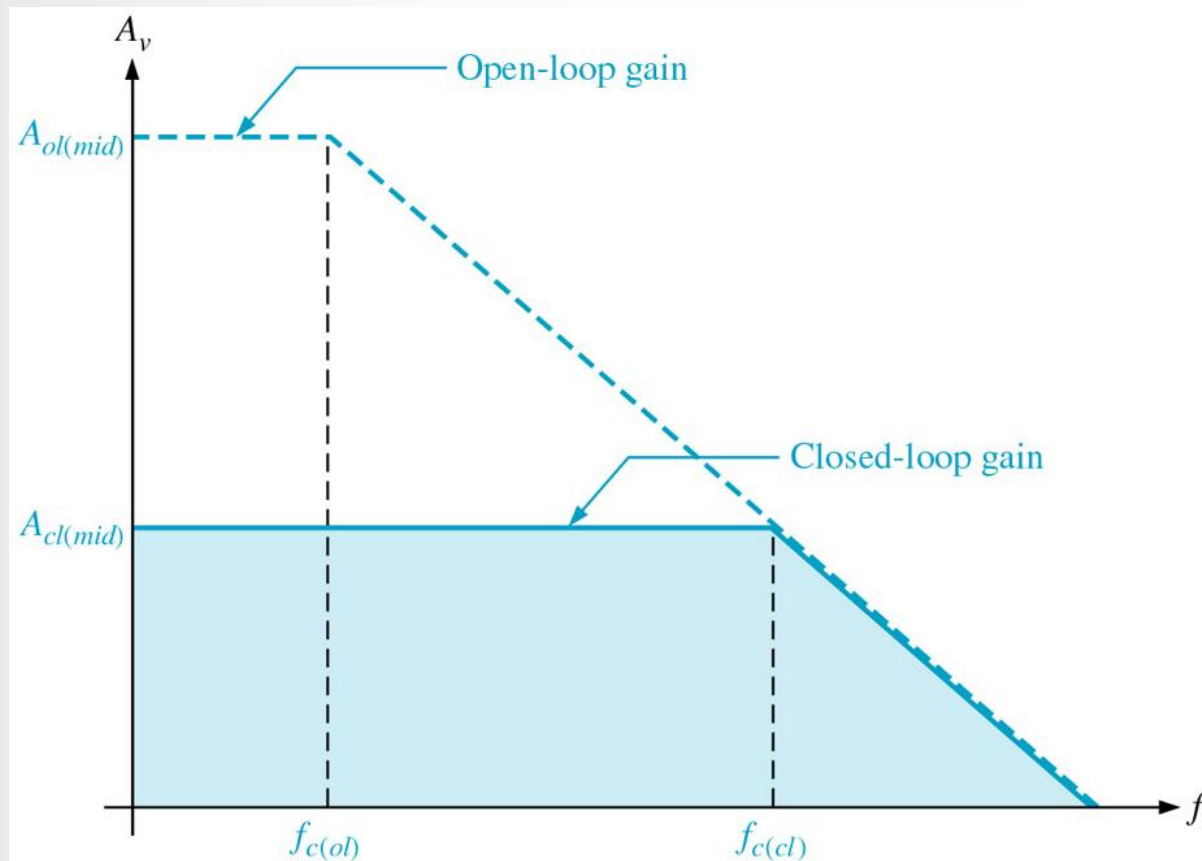


(c) Composite response for an uncompensated op-amp



Fundamental (XIII)

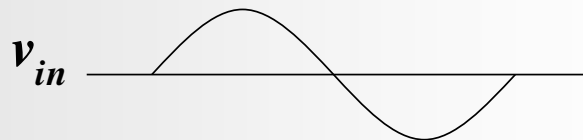
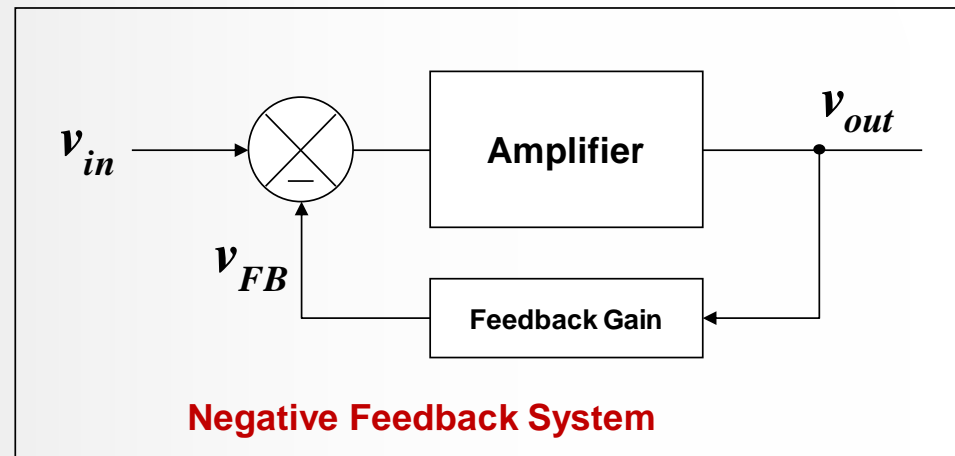
❖ Closed-Loop의 Gain & Bandwidth





Fundamental (XIV)

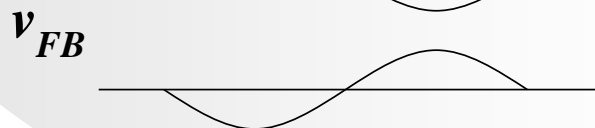
❖ Phase Margin, Gain Margin, Stability



(180° 위상차 발생 시)
Positive Feedback



Unstable



Negative Feedback
(위상차가 180° 이하 일 때)



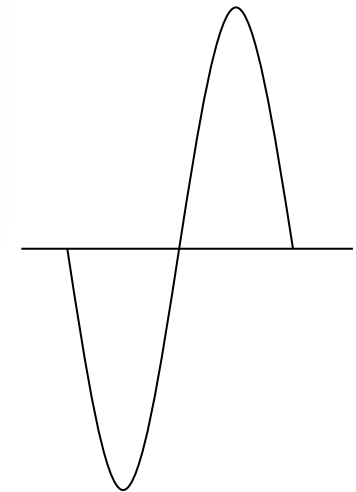
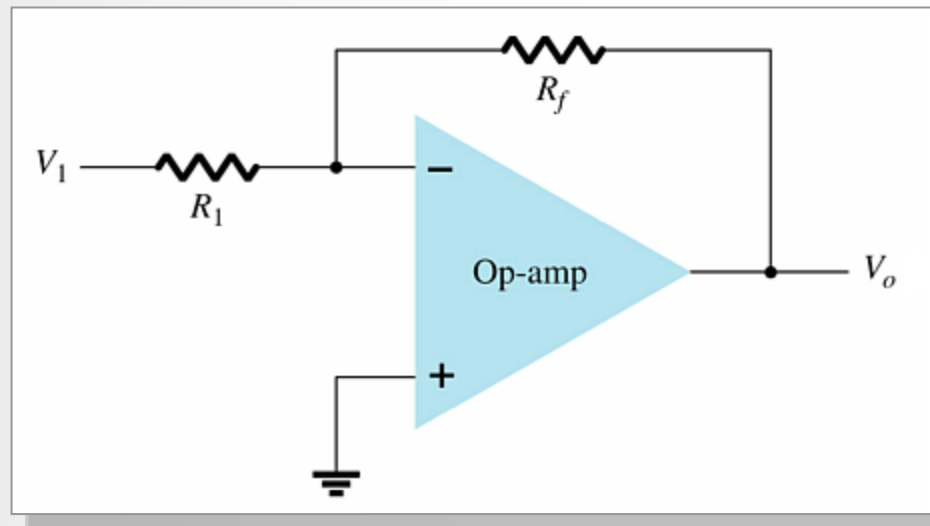
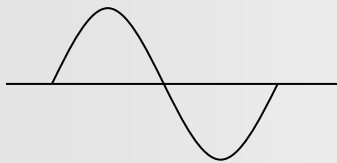
Stable



Inverting Amplifier (I)

❖ 반전 증폭기의 입출력 관계

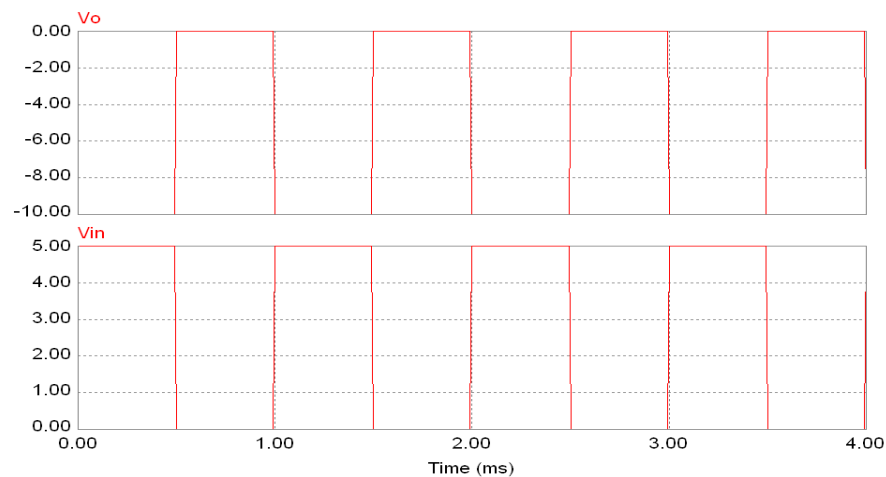
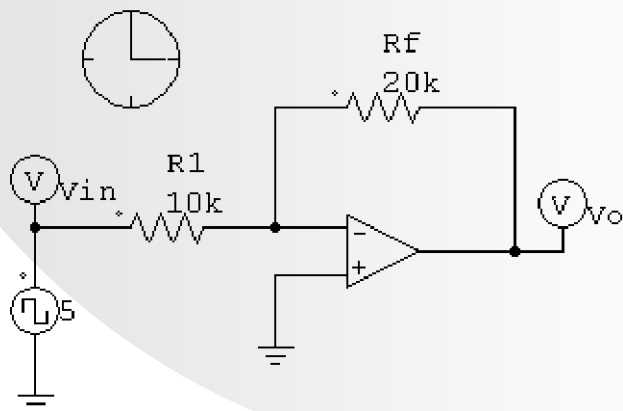
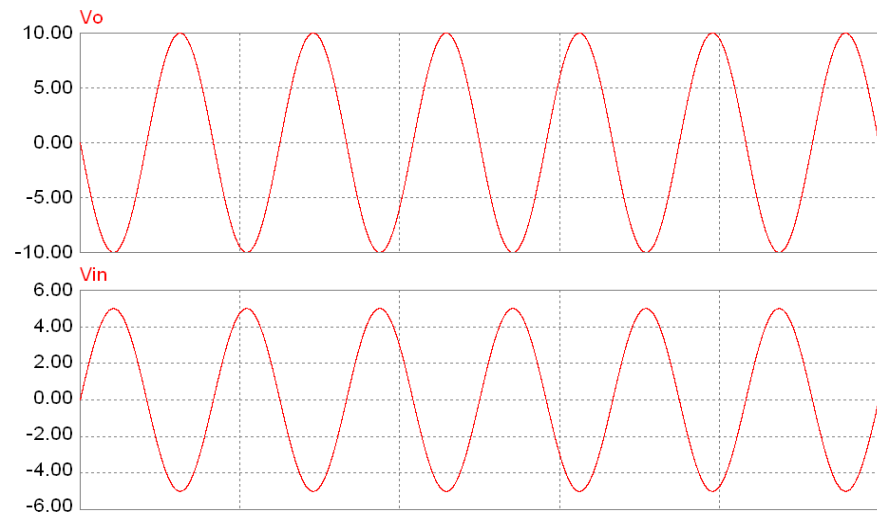
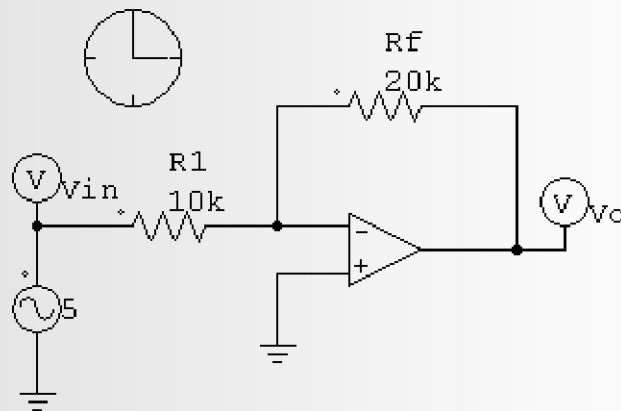
$$V_o = -\frac{R_f}{R_1} \cdot V_1 \quad \text{or} \quad \frac{V_o}{V_1} = -\frac{R_f}{R_1}$$





Inverting Amplifier (II)

❖ 반전 증폭기 시뮬레이션



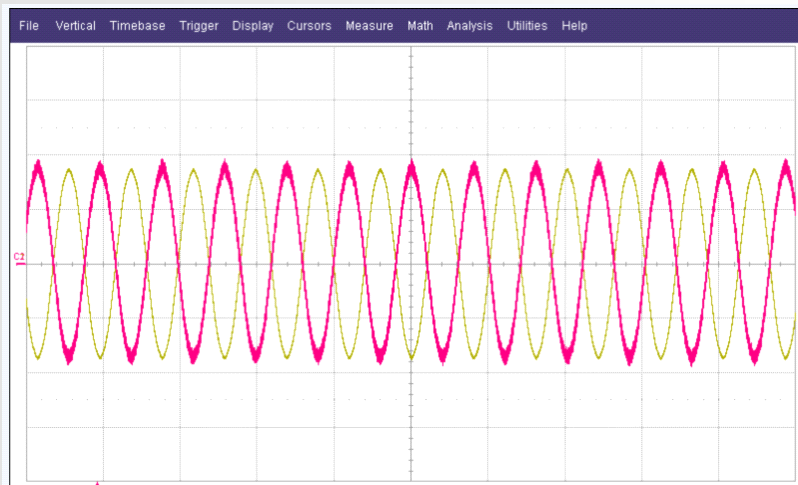


Inverting Amplifier (III)

❖ 반전 증폭기 실험파형

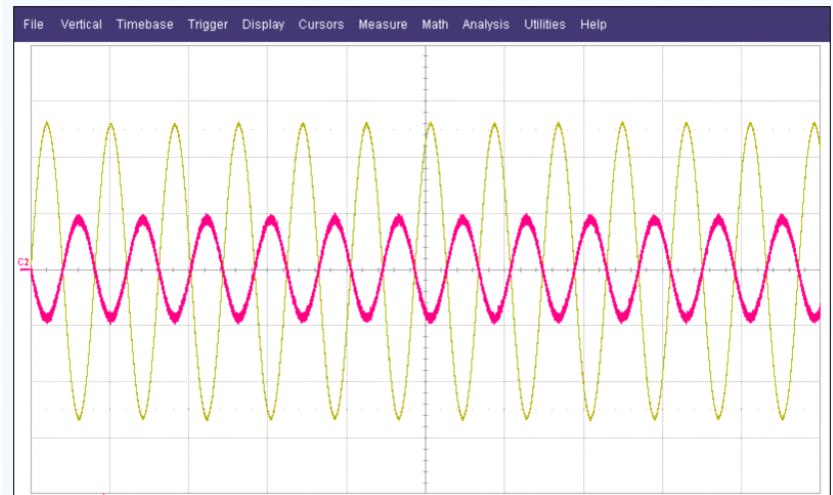
입력 전압

출력 전압



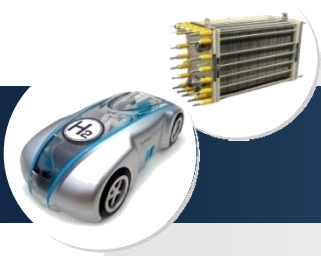
저항을 각각
 $R_1 = 10k\Omega$
 $R_f = 10k\Omega$

출력측 증폭도 $G=1$



저항을 각각
 $R_1 = 10k\Omega$
 $R_f = 10k\Omega$

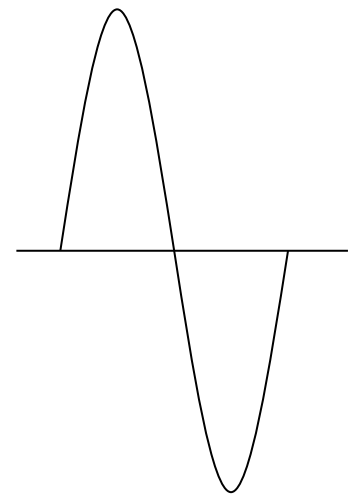
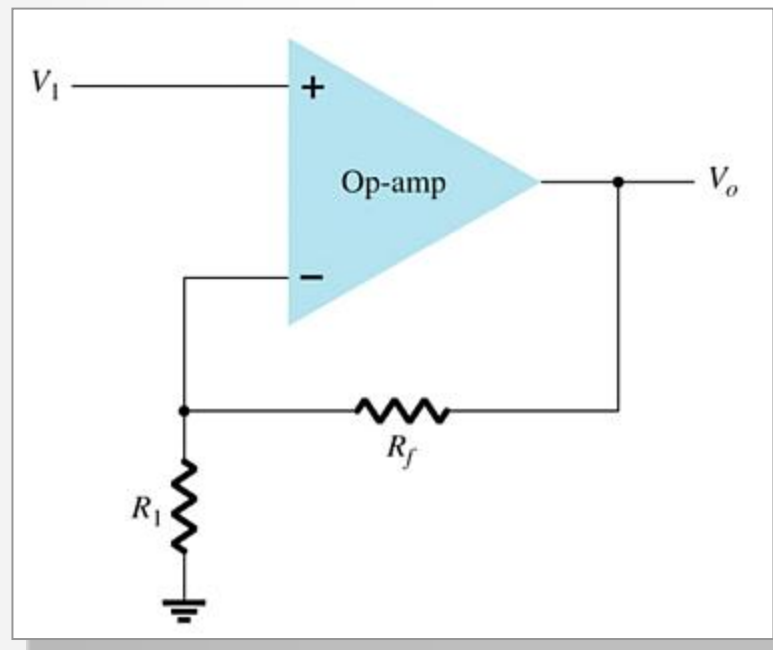
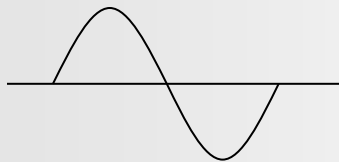
출력측 증폭도 $G=3$



Non-Inverting Amplifier (I)

❖ 비반전 증폭기의 입출력 관계

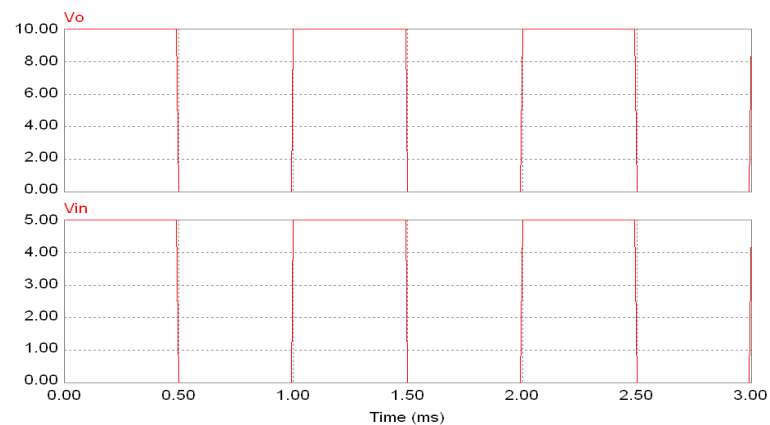
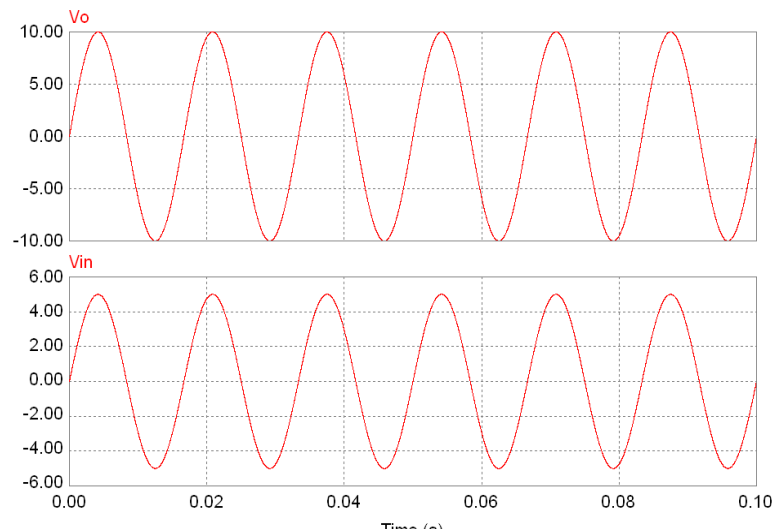
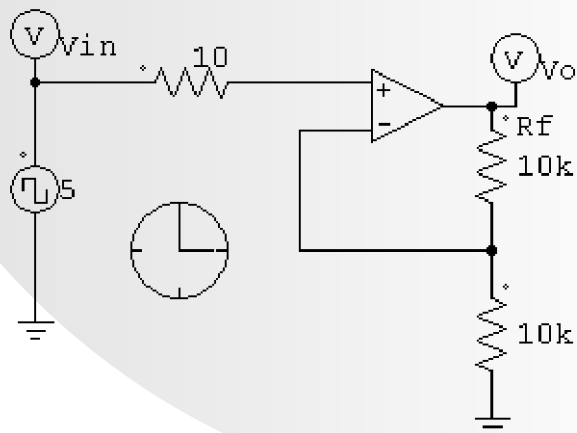
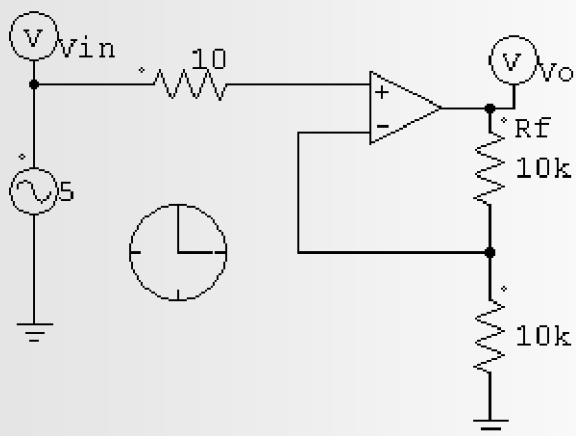
$$V_o = \left(1 + \frac{R_f}{R_1}\right) \cdot V_1 \quad \text{or} \quad \frac{V_o}{V_1} = \left(1 + \frac{R_f}{R_1}\right)$$





Non-Inverting Amplifier (II)

❖ 비반전 증폭기 시뮬레이션



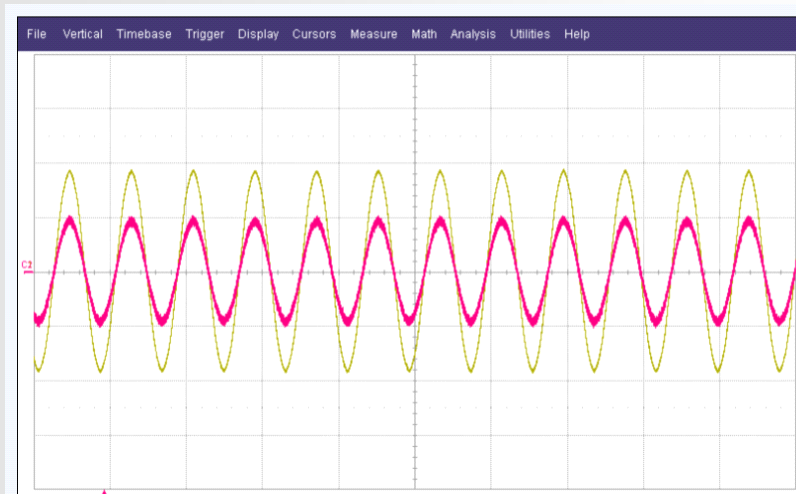


Non-Inverting Amplifier (III)

❖ 비반전 증폭기 실험파형

입력 전압

출력 전압



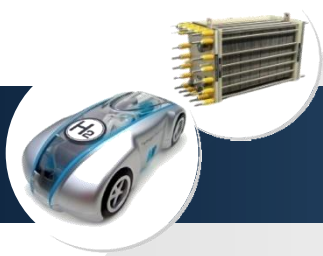
저항을 각각
 $R_1 = 10\text{ k}\Omega$
 $R_f = 10\text{ k}\Omega$

출력측 증폭도 $G=2$



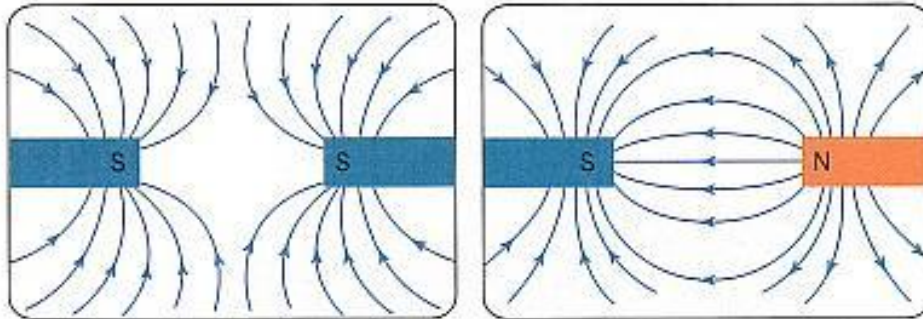
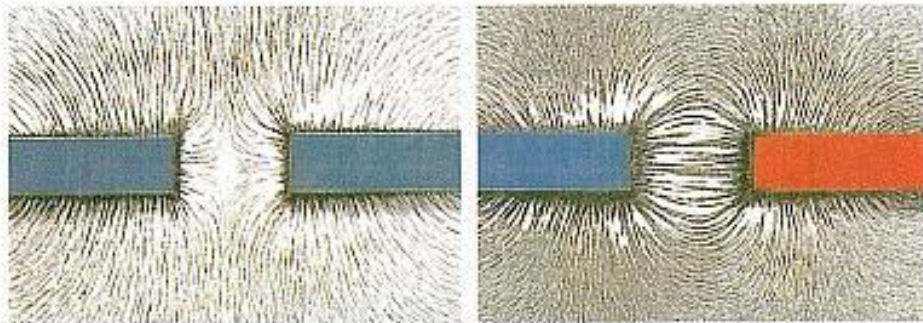
저항을 각각
 $R_1 = 10\text{ k}\Omega$
 $R_f = 10\text{ k}\Omega$

출력측 증폭도 $G=4$



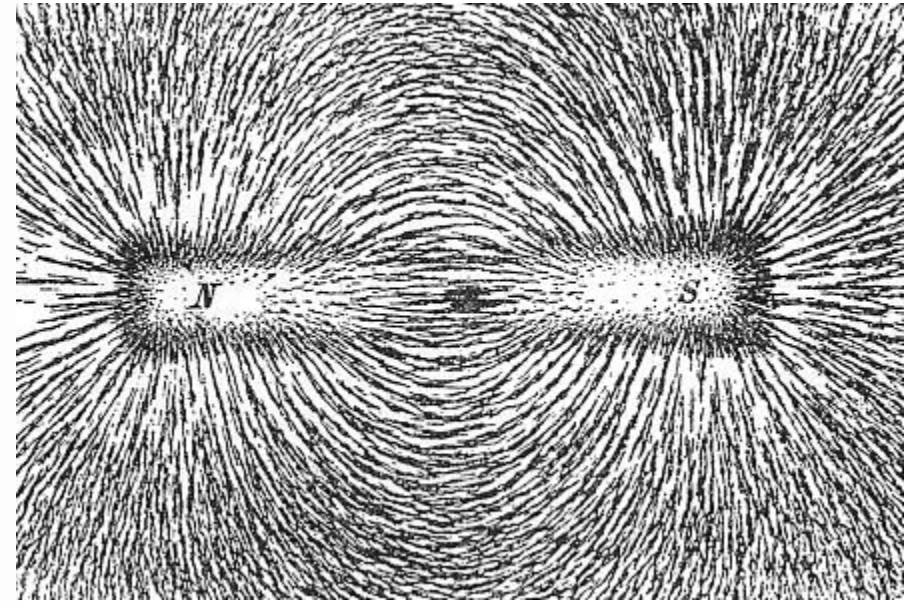
자성소자

❖ 자속 (Magnetic Flux)



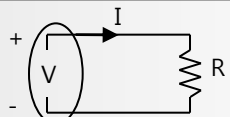
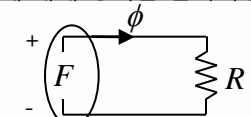
예 S극과 S극을 가까이할 때
막대 자석 주위의 자기장과 자기력선

예 S극과 N극을 가까이할 때
www.encyber.com





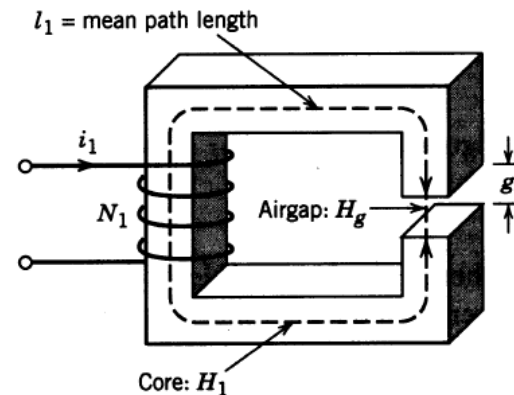
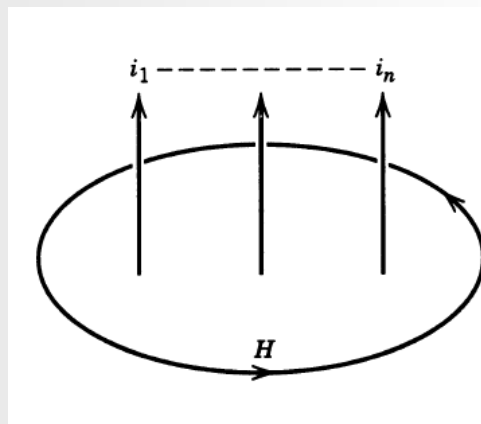
전기회로와 자기회로

	Electric Circuit	Unit	Magnetic Circuit	Unit
Driving force	EMF (Electromotive Force) (V): 기전력	V	MMF (Magnetomotive Force): 기자력 (F)	At
Response	Current (I): 전하의 이동 (전위차가 높은 곳에서 낮은 곳으로)	A	Flux: 임의의 표면적을 통과하는 자기력선의 수에 비례하는 양 (ϕ)	Wb
Impedance	Resistance (R): 전기저항 (전류의 흐름을 방해하려는 성질의 크기)	Ω	Reluctance: 자기회로에서 자기력선속에 대해 생기는 전기저항력 (R)	1/H
Equivalent circuit	 $V=IR$		 $F = \phi R$	
Field intensity relationship	$\oint \vec{E} \cdot d\vec{l} = V$	V	$\oint \vec{H} \cdot d\vec{l} = I$	A
Potential difference	$V = IR$	V	$F = \phi R = NI$	At
Other relations	$J = \frac{I}{A} = \frac{V}{AR} = \frac{EI}{A(\rho l/A)} = \frac{E}{\rho} = \sigma E$ $E = \rho J = J / \sigma$ <p> J: 전류밀도 ρ: 저항률 σ: 전도율 </p>	A/m^2 $\Omega \cdot m$ $1/(\Omega \cdot m)$	$B = \frac{\phi}{A} = \frac{F}{AR} = \frac{Hl}{A(l/\mu A)}$ $= \mu H = H / \nu$ $H = B / \mu = \nu B$ <p> B: 자속밀도 μ: 투자율 ν: 자기저항률 </p>	T or Wb/m ² H/m m/H
Admittance	conductance	S	permeance $P = 1/R$	H



자기회로 (I)

❖ 암페어의 주회적분 법칙 (Ampere's Law)



- 전류가 흐르는 도선 주변에 H 크기의 자계 발생
- 자계 H [A/m]에 대하여 선적분하면 폐곡선 내를 통과하는 전체 전류와 같음

$$\oint H \cdot dl = \sum i$$

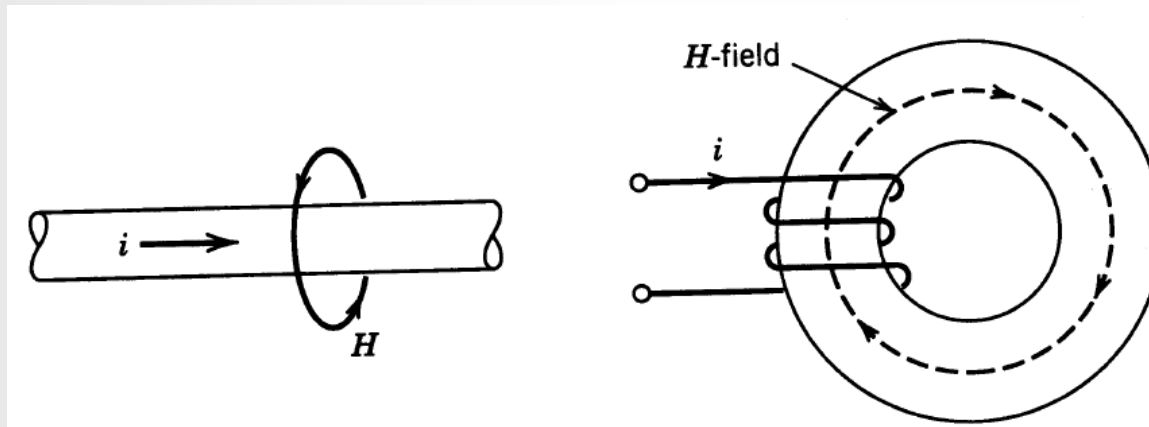
- 실제 자성체에 권선이 감겨있고 전류가 흐를 경우 발생하는 자계와 기자력의 관계

$$\begin{aligned} \sum_k H_k l_k &= \sum_m N_m i_m \\ \rightarrow H_1 l_1 + H_g l_g &= N_1 i_1 \end{aligned}$$



자기회로 (II)

❖ 암페어의 오른나사 법칙 (Ampere's Right Hand Rule)

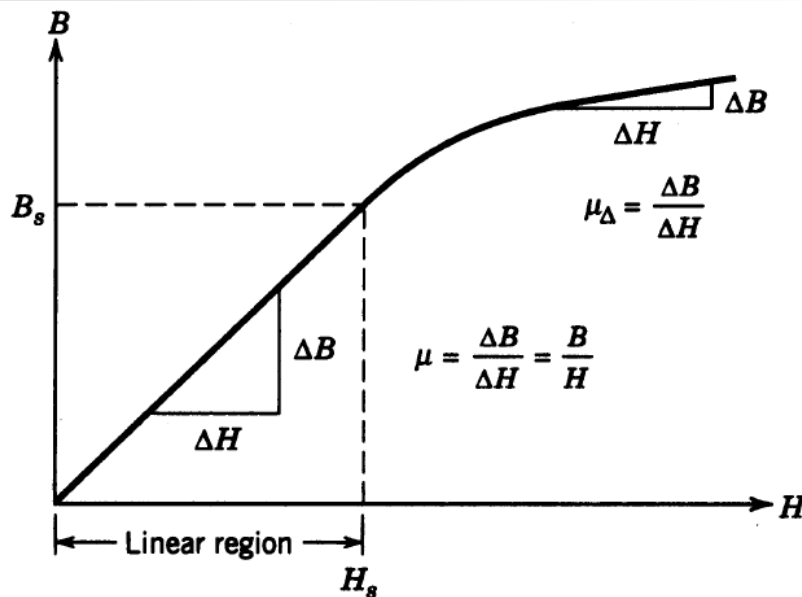


- 권선에 흐르는 전류의 방향 or 권선방향에 따라 자계의 방향 결정
- 오른손 법칙으로 결정됨



자기회로 (III)

❖ B-H Curve



$$B = \mu H$$

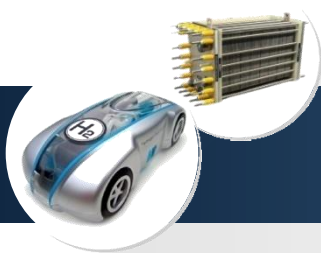
where, B : flux density [Wb/m^2] or [T]

μ : permeability [H/m] → 투자율

where, $\mu = \mu_0 \cdot \mu_r$

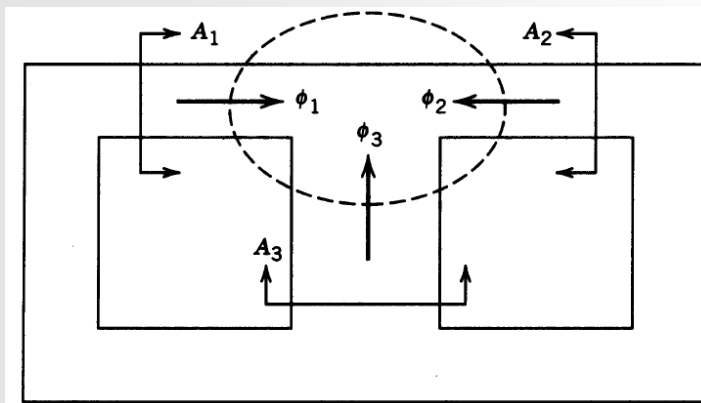
($\mu_0 = 4\pi \times 10^{-7}$, $\mu_r = 500 \sim 3000$, iron)

- 투자율이란 : 자속을 통과시키는 비율 (투자율이 크면 자속을 많이 흘릴 수 있음)
- 공기, 철심, 페라이트 등의 투자율
- 히스테리시스 곡선 (B-H or ϕ -I 커브) & 포화



자기회로 (IV)

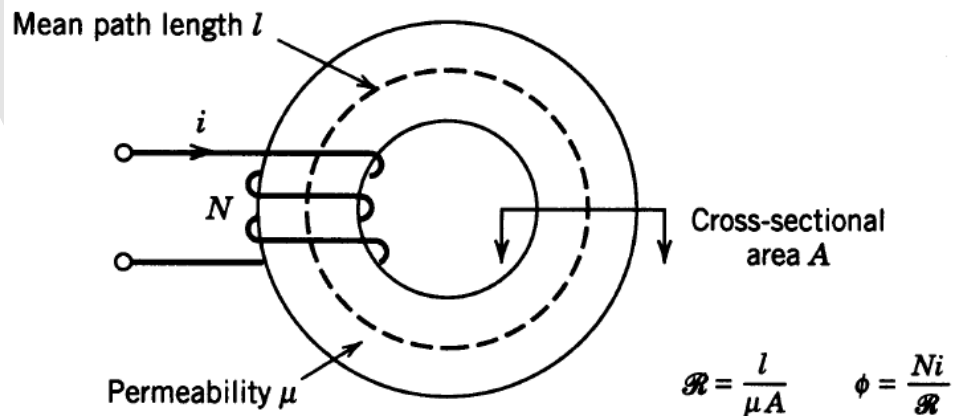
❖ Continuity of Flux Lines and Concept of Magnetic Reluctance



$$\phi = \iint_{A(\text{closed surface})} \mathbf{B} \cdot d\mathbf{A} = 0$$

$$i.e. > \phi_1 + \phi_2 + \phi_3 = 0$$

- 페루프임 (closed loop): 회전하는 형태
- 발산하지 않음
- 스스로 magnetic flux를 만드는 것 없음



$$F = Ni = \mathcal{R} \phi$$

$$\therefore \text{Magnetic reluctance: } \phi = \frac{Ni}{\mathcal{R}}$$

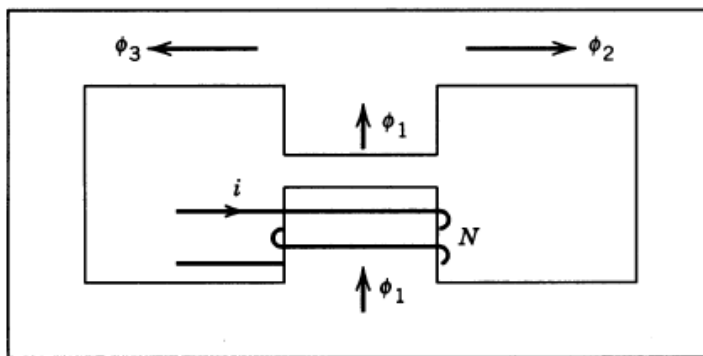
$$\text{Permeance: } P = \frac{1}{\mathcal{R}}$$

(전기회로의 도전율과 같은 개념)

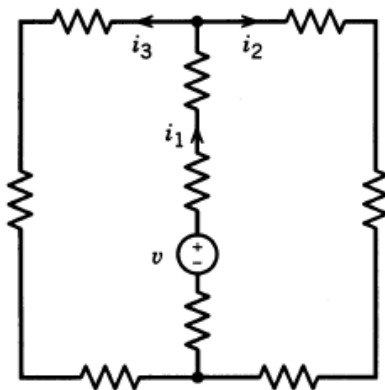


자기회로 (V)

❖ Continuity of Flux Lines

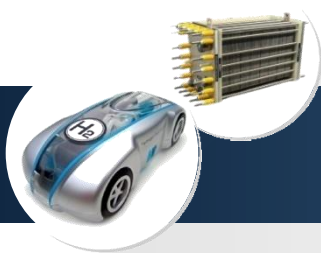


(a)



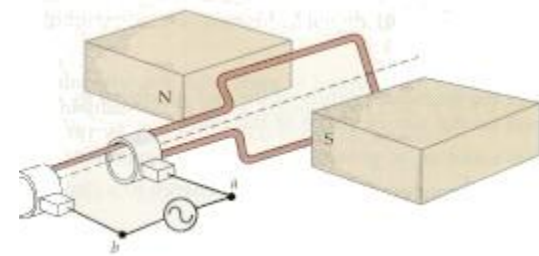
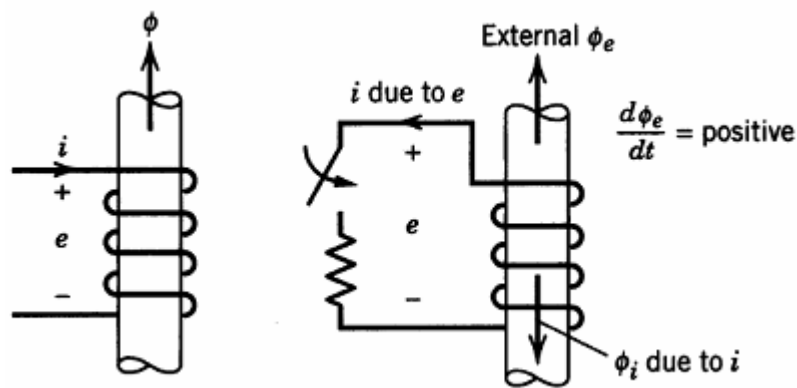
<i>Magnetic Circuit</i>	<i>Electric Circuit</i>
mmf Ni	v
Flux ϕ	i
reluctance \mathcal{R}	R
permeability μ	$1/\rho$, where ρ = resistivity

<i>Magnetic</i>	<i>Electrical (dc)</i>
$\frac{Ni}{\phi} = \mathcal{R} = \frac{l}{\mu A}$	Ohm's law: $\frac{v}{i} = R = \frac{l}{A/\rho}$
$\phi \sum_k \mathcal{R}_k = \sum_m N_m i_m$	Kirchhoff's voltage law: $i \sum_k R_k = \sum_m v_m$
$\sum \phi_k = 0$	Kirchhoff's current law: $\sum_k i_k = 0$



전자기 유도법칙 (I)

❖ Faraday's Law

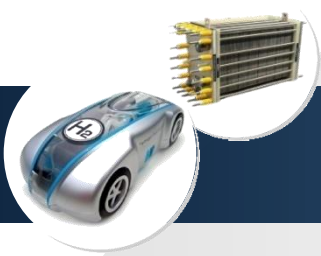


▪ 패러데이의 전자기유도법칙

- 1820년 Oersted: 전류가 흐르는 도선에 의해 자기가 만들어지는 사실 발견
- Faraday & Henry: 코일에 자석을 넣었다 뺐다 하면 도선에 전류가 흐르는 현상 발견
- 코일 내 자기장의 변화가 생기면 기전력 유도되는 현상 (물리적으로 뉴턴 2 & 3법칙으로 설명 가능)

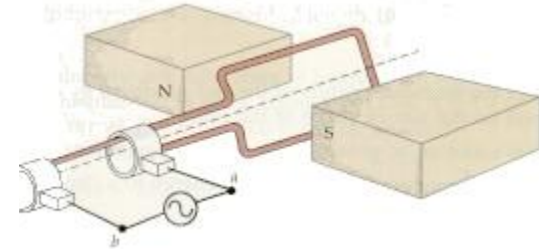
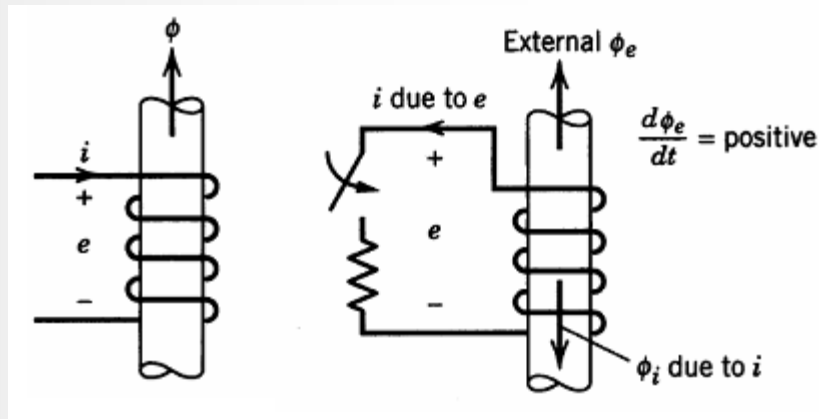
$$e = N \frac{d\phi}{dt}$$

- 유도되는 기전력의 크기는 자석의 운동 속도 뿐 아니라 권선의 감은 수에도 비례함
- 발전기의 동작원리임 * <http://www.youtube.com/watch?v=stUDqGzpev8>



전자기 유도법칙 (II)

❖ Lenz's Law



▪ 렌츠의 법칙

- 시간에 따라 변화되는 자계에 의해 발생된 유기기전력은 이를 방해하려는 방향으로 유기됨

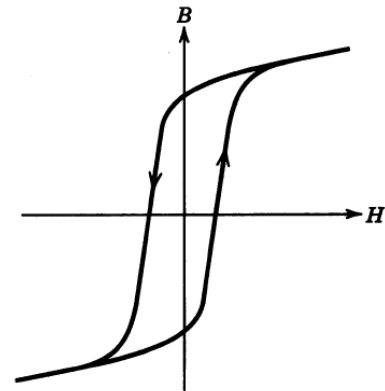
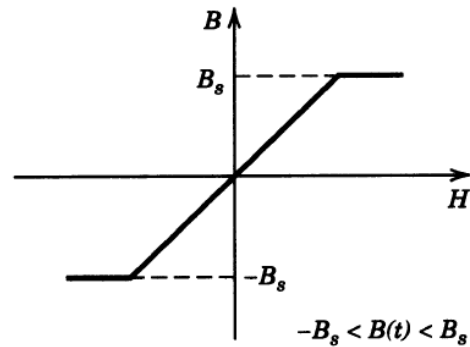
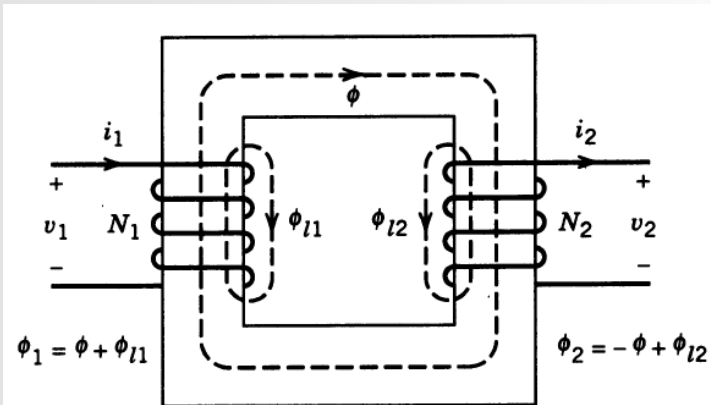
$$e = -N \frac{d\phi}{dt}$$

- http://www.youtube.com/watch?v=WHCwgc_xs3s&feature=related



변압기 (I)

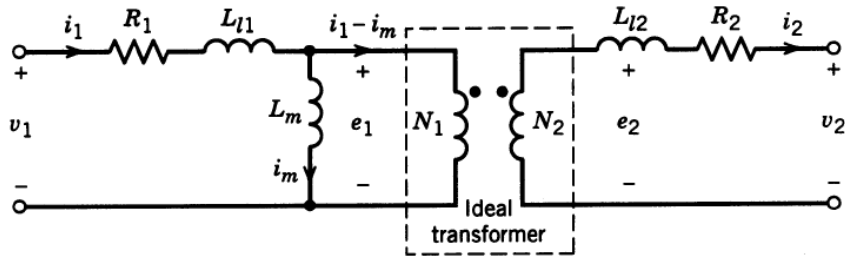
❖ 변압기 구조 및 특성곡선



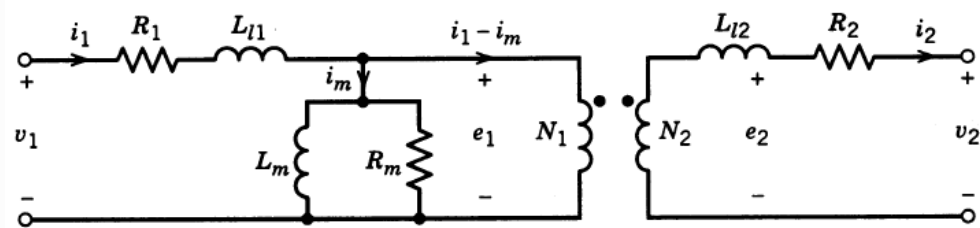
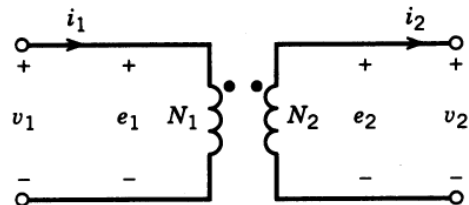


변압기 (II)

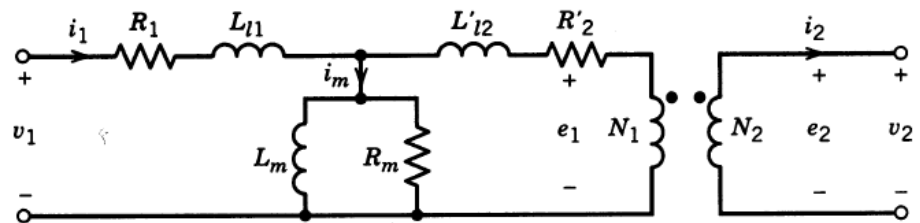
❖ 변압기 구조 등가회로



(a)

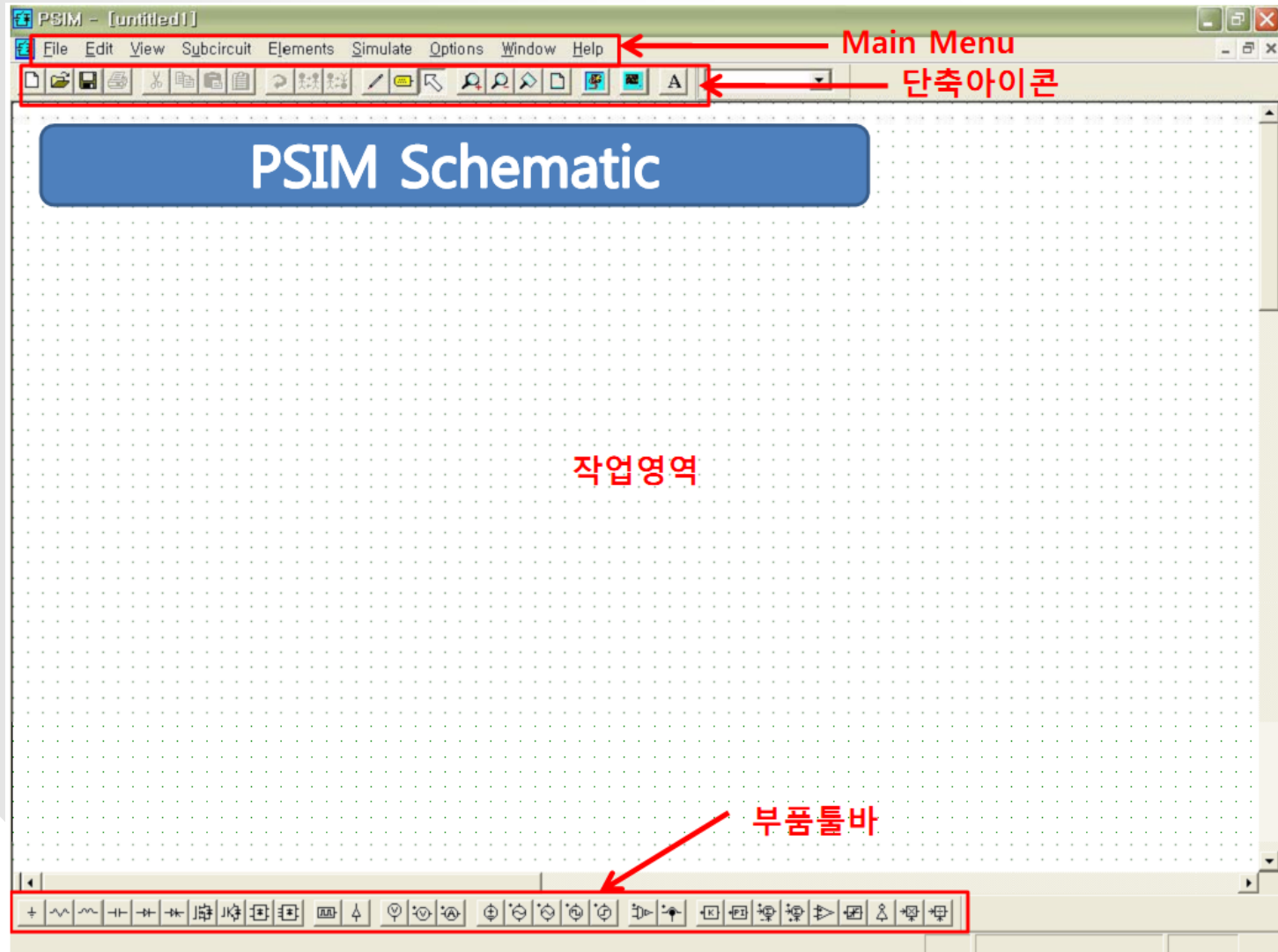


(a)



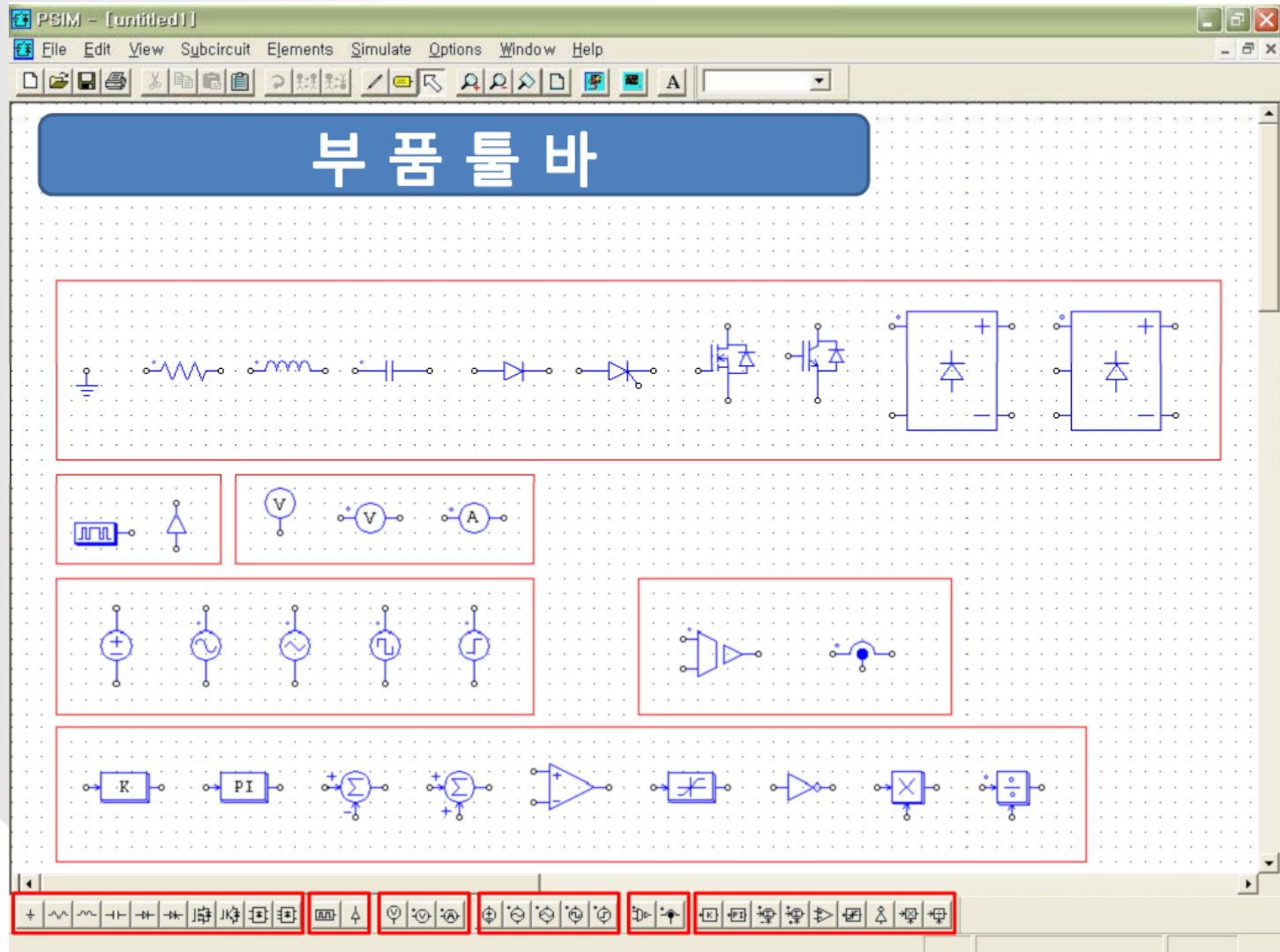


Fundamental





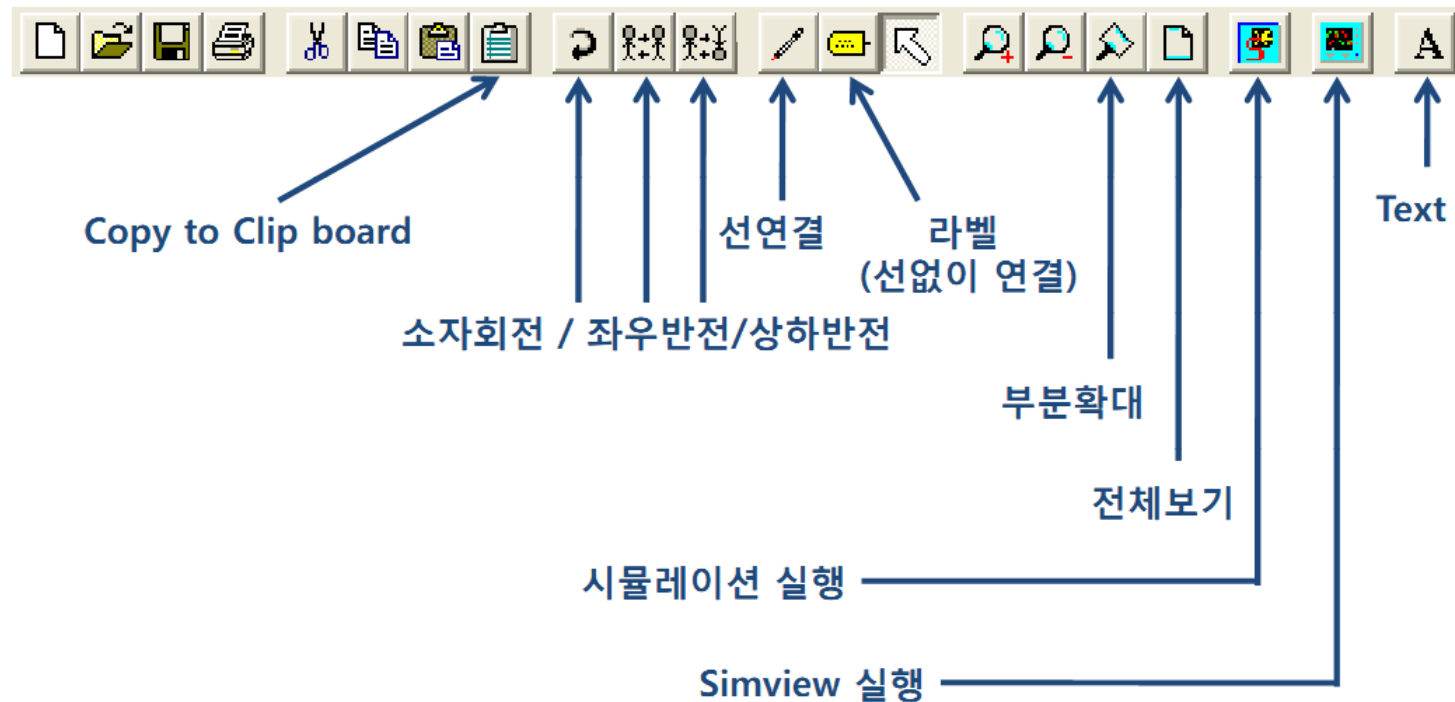
Fundamental





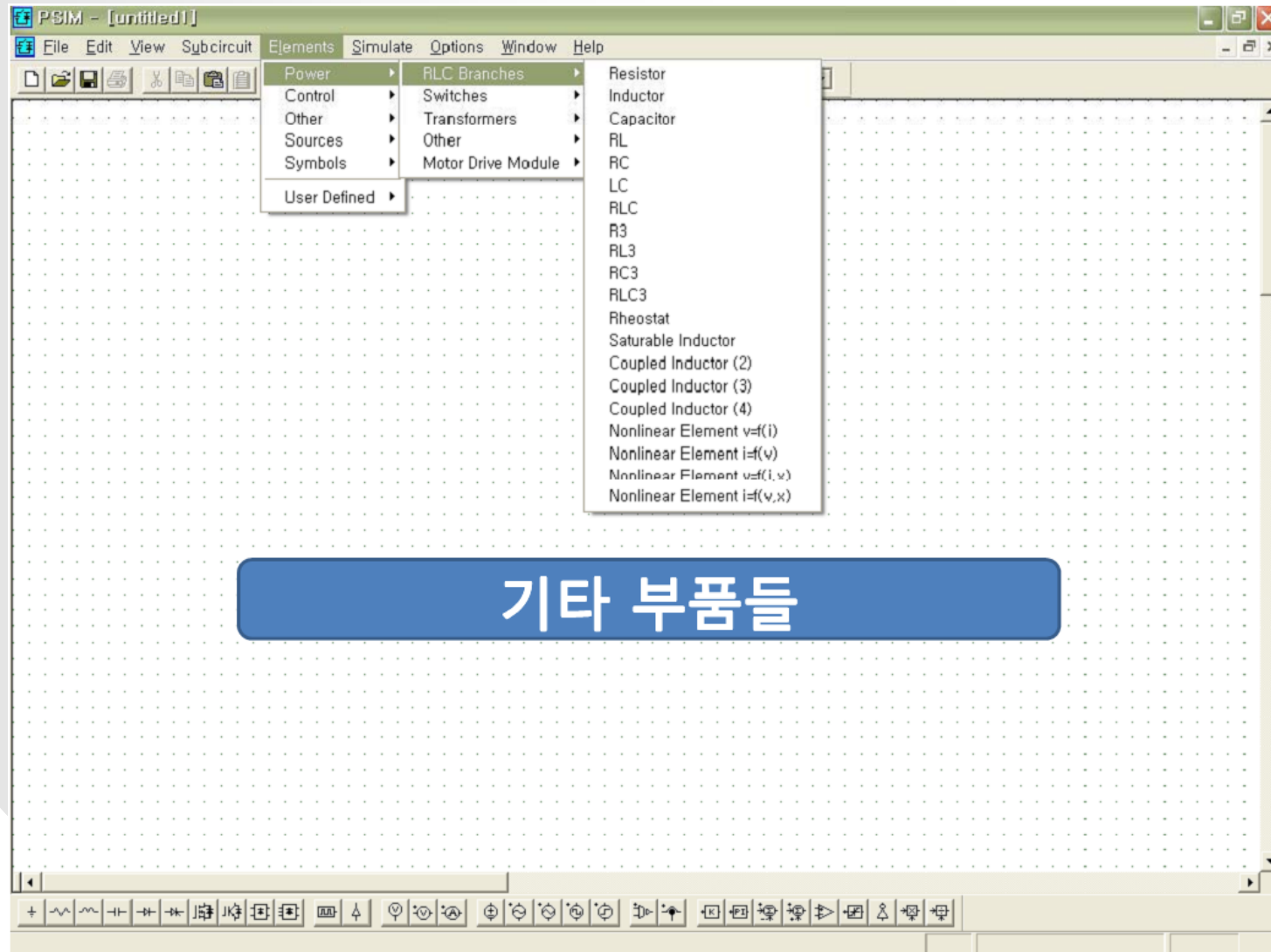
Fundamental

단축아이콘





Fundamental

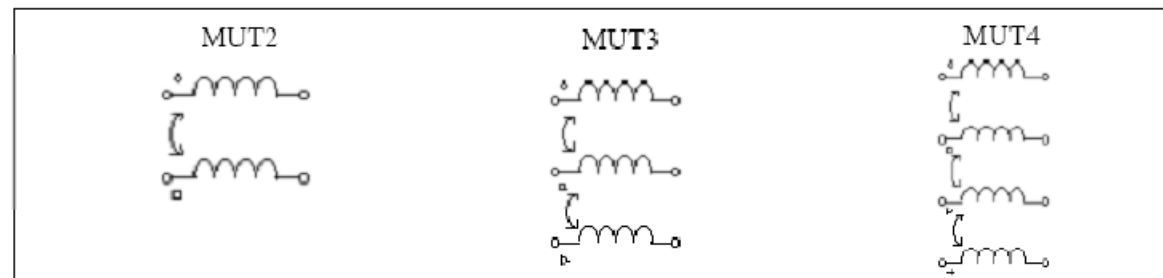
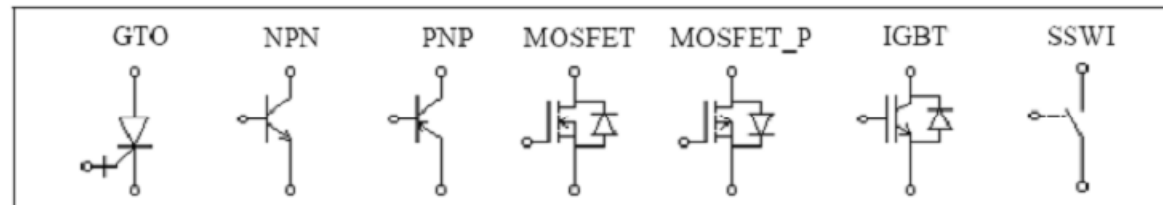
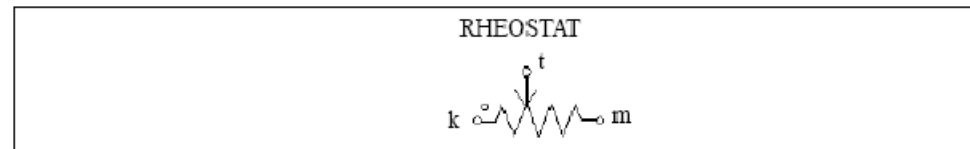
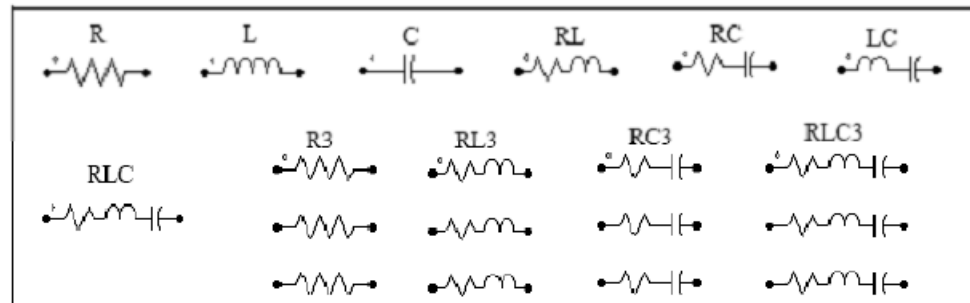


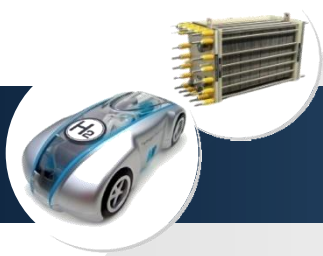
기타 부품들



PSIM Component

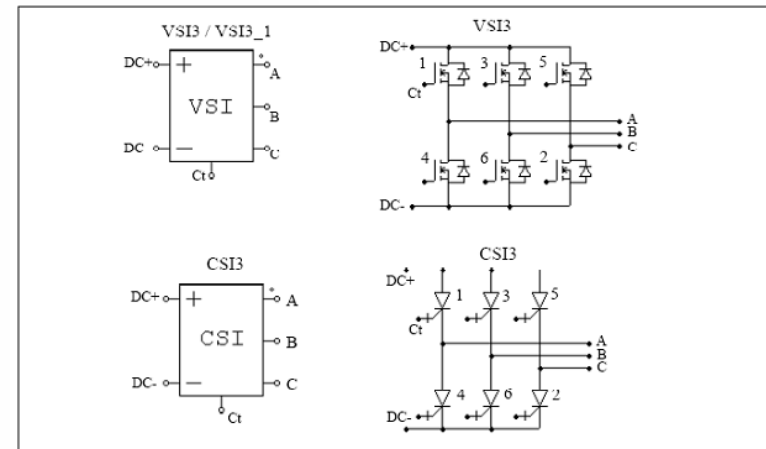
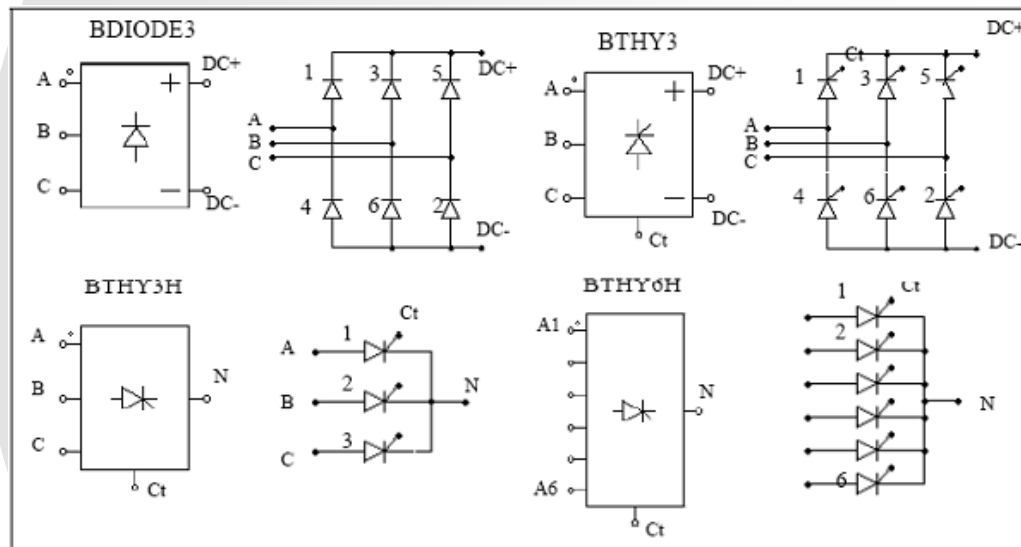
❖ RLC & Switch





PSIM Component

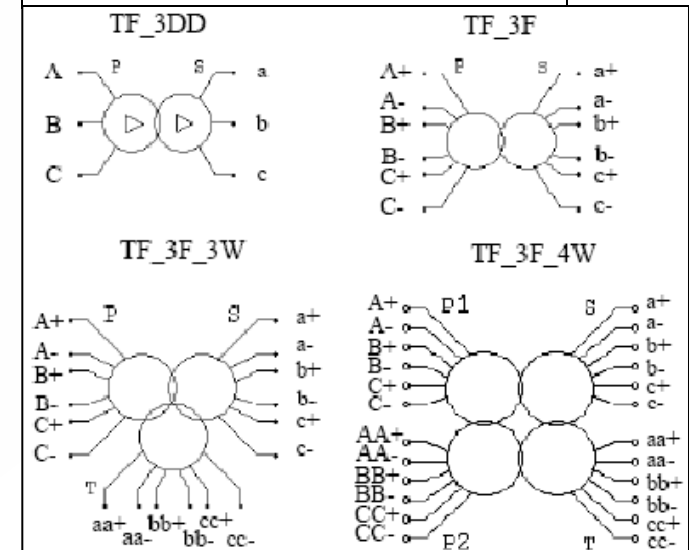
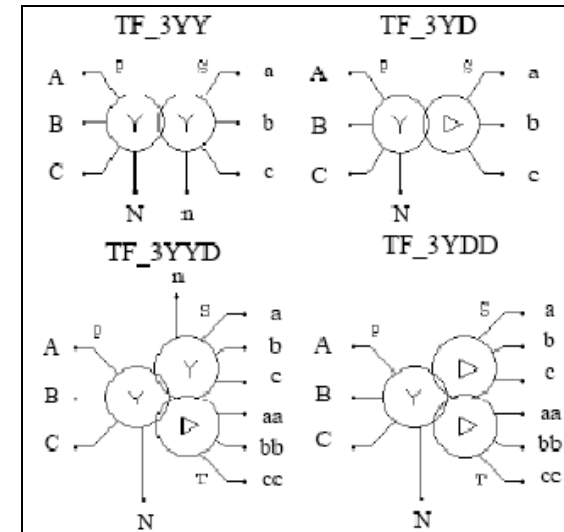
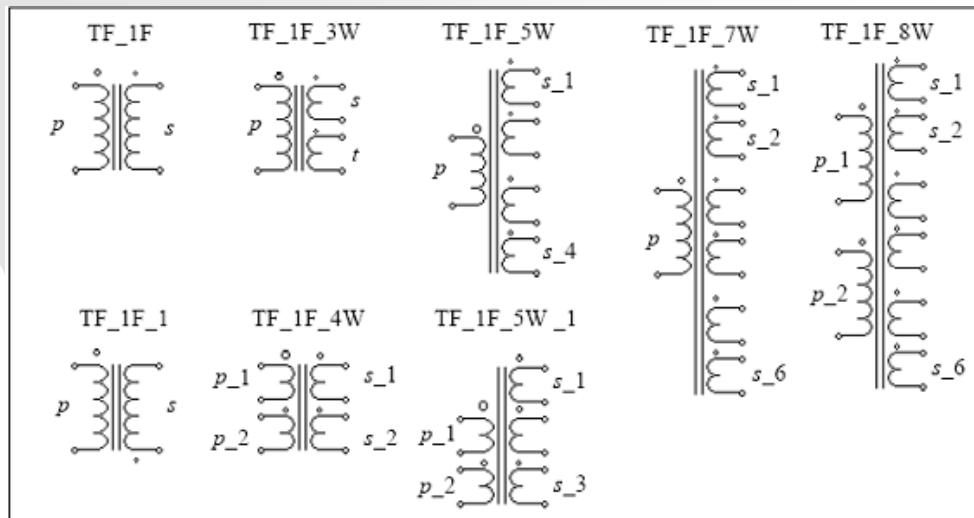
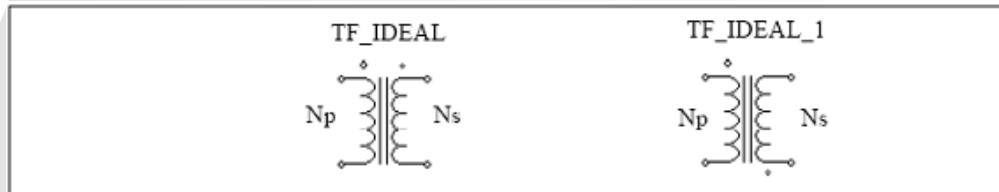
❖ Diode & Thyristor





PSIM Component

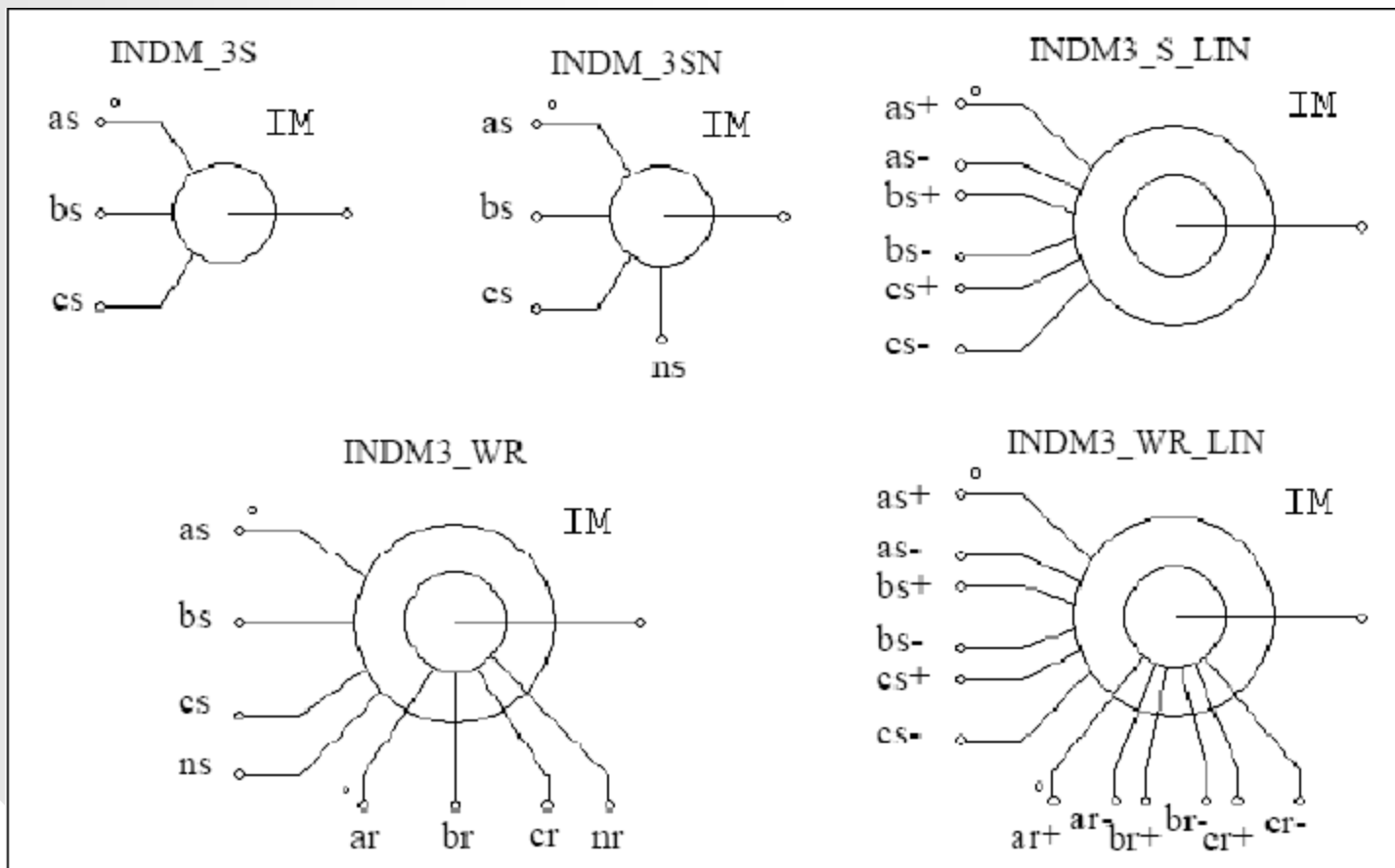
❖ Transformer

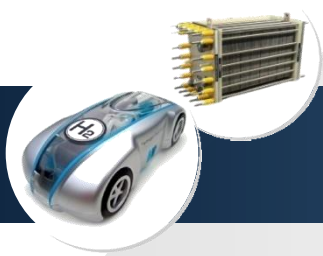




PSIM Component

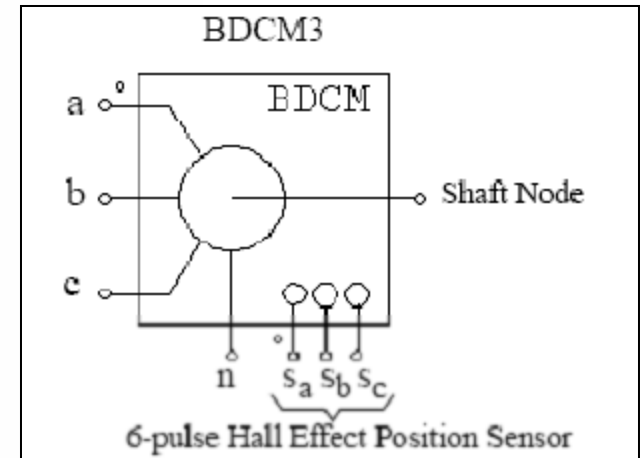
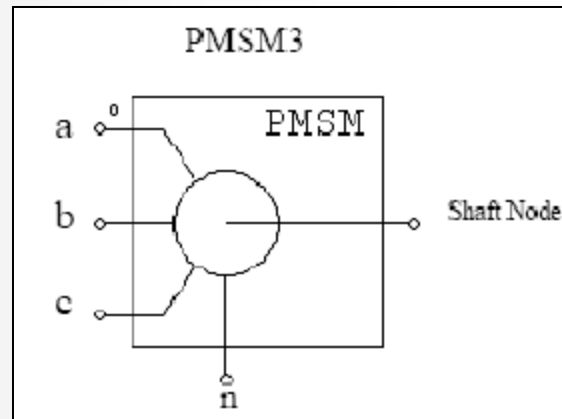
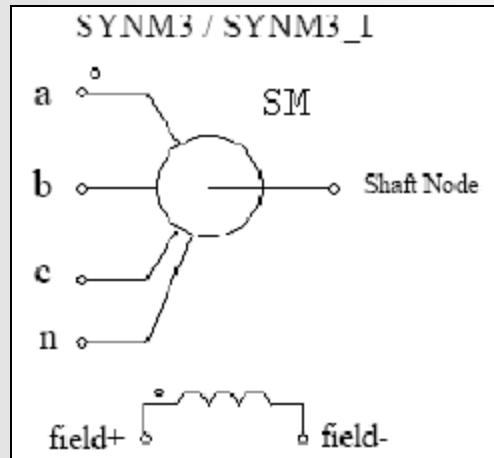
❖ Induction Motors





PSIM Component

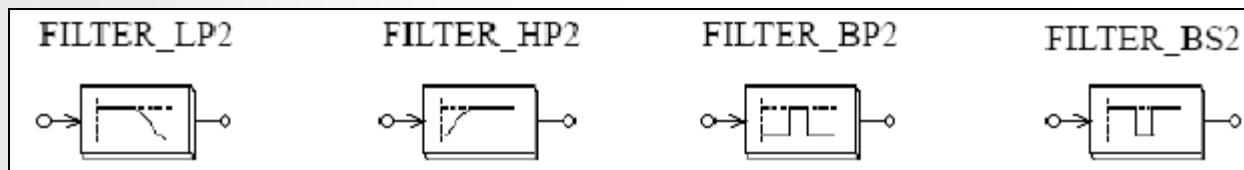
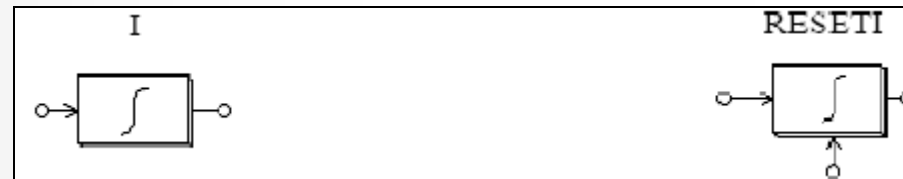
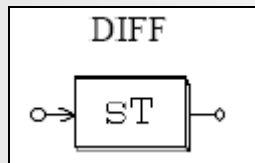
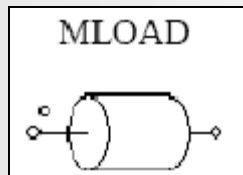
❖ PMSM & BLDC

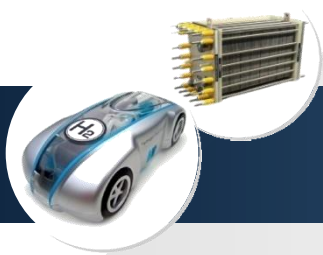




PSIM Component

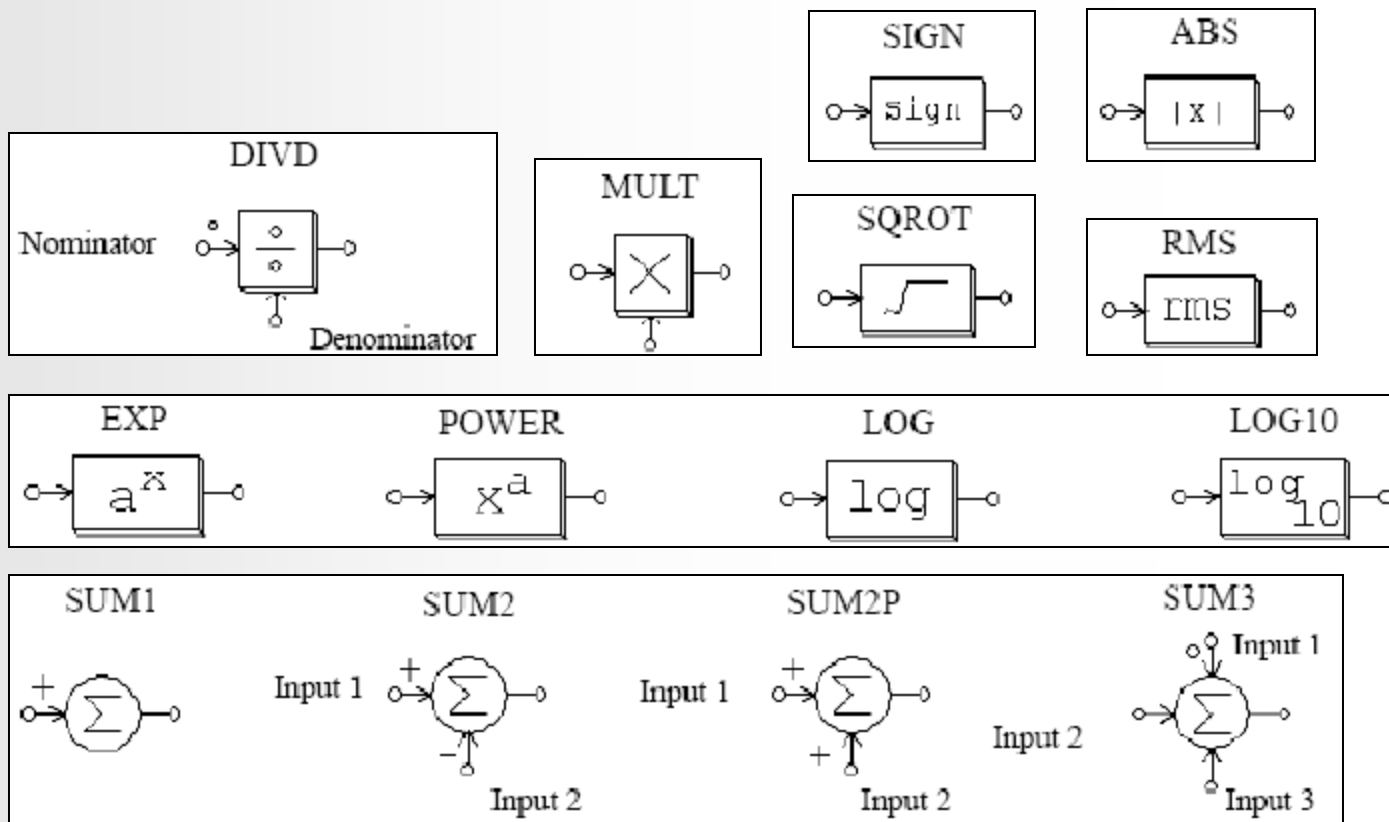
❖ Motor Drive ETC





PSIM Component

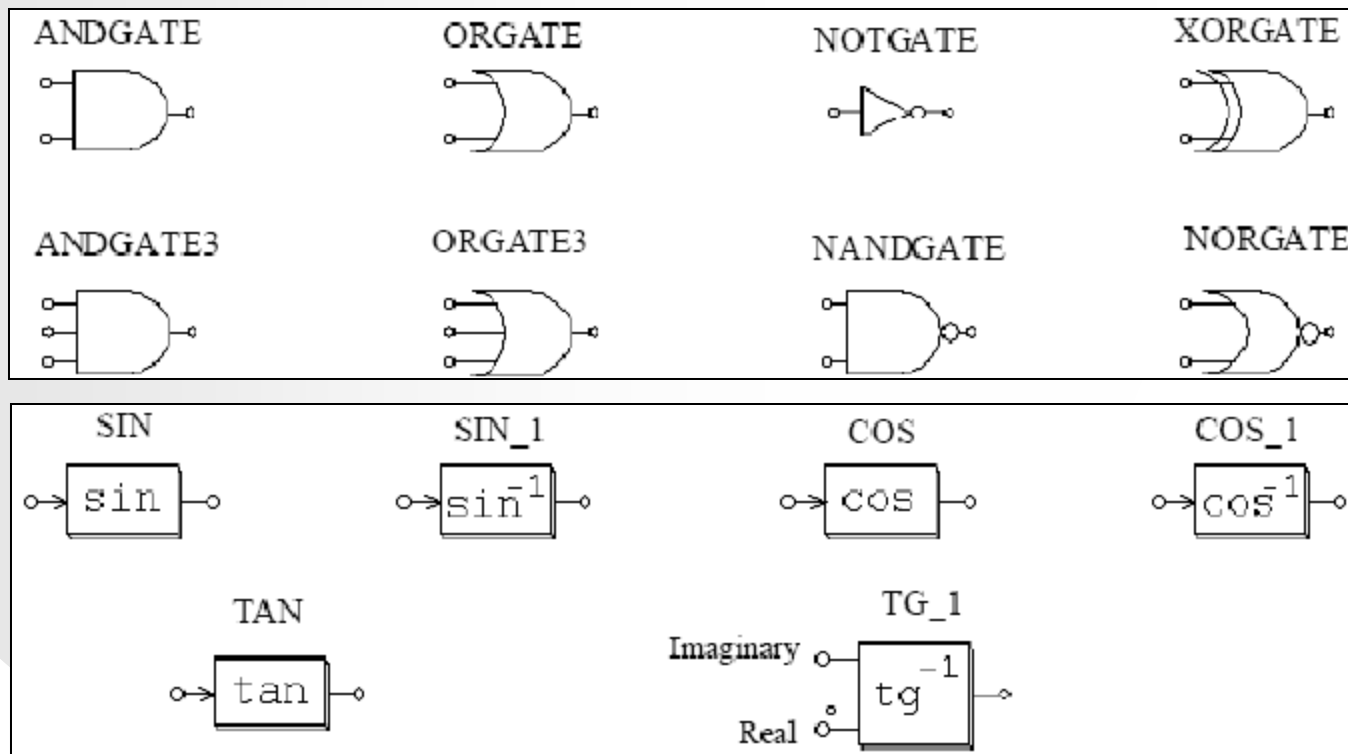
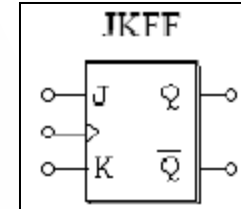
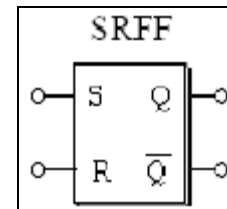
❖ Mathematical Operation





PSIM Component

❖ Trigonometry & Logic Function





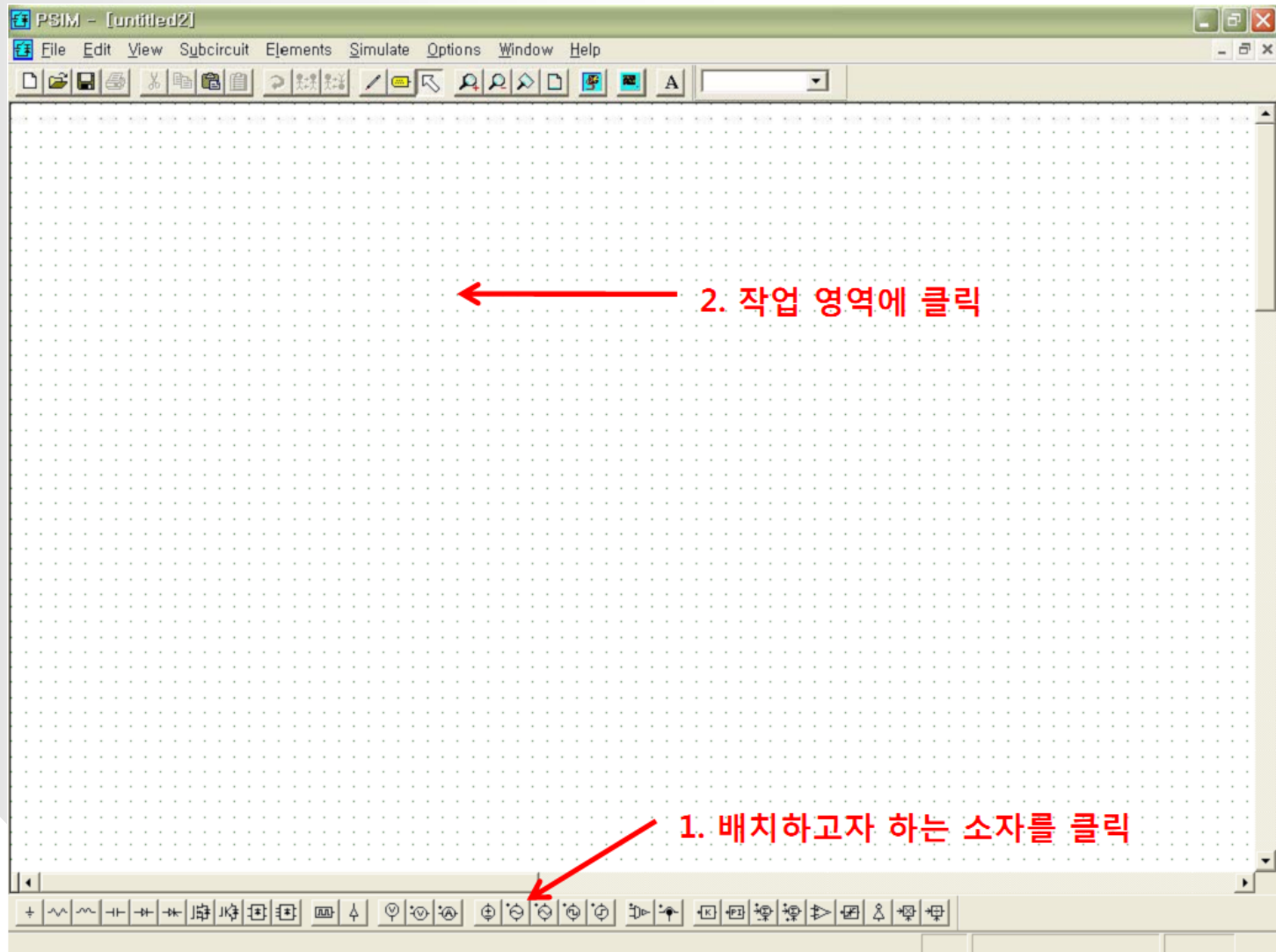
Simulation

❖ 시뮬레이션 진행과정

- 부품배치
- 결선
- 계측기배치 및 결선
- 소자 파라미터 선정
- 시뮬레이션 컨트롤러
- 시뮬레이션 시작
- 파형분석

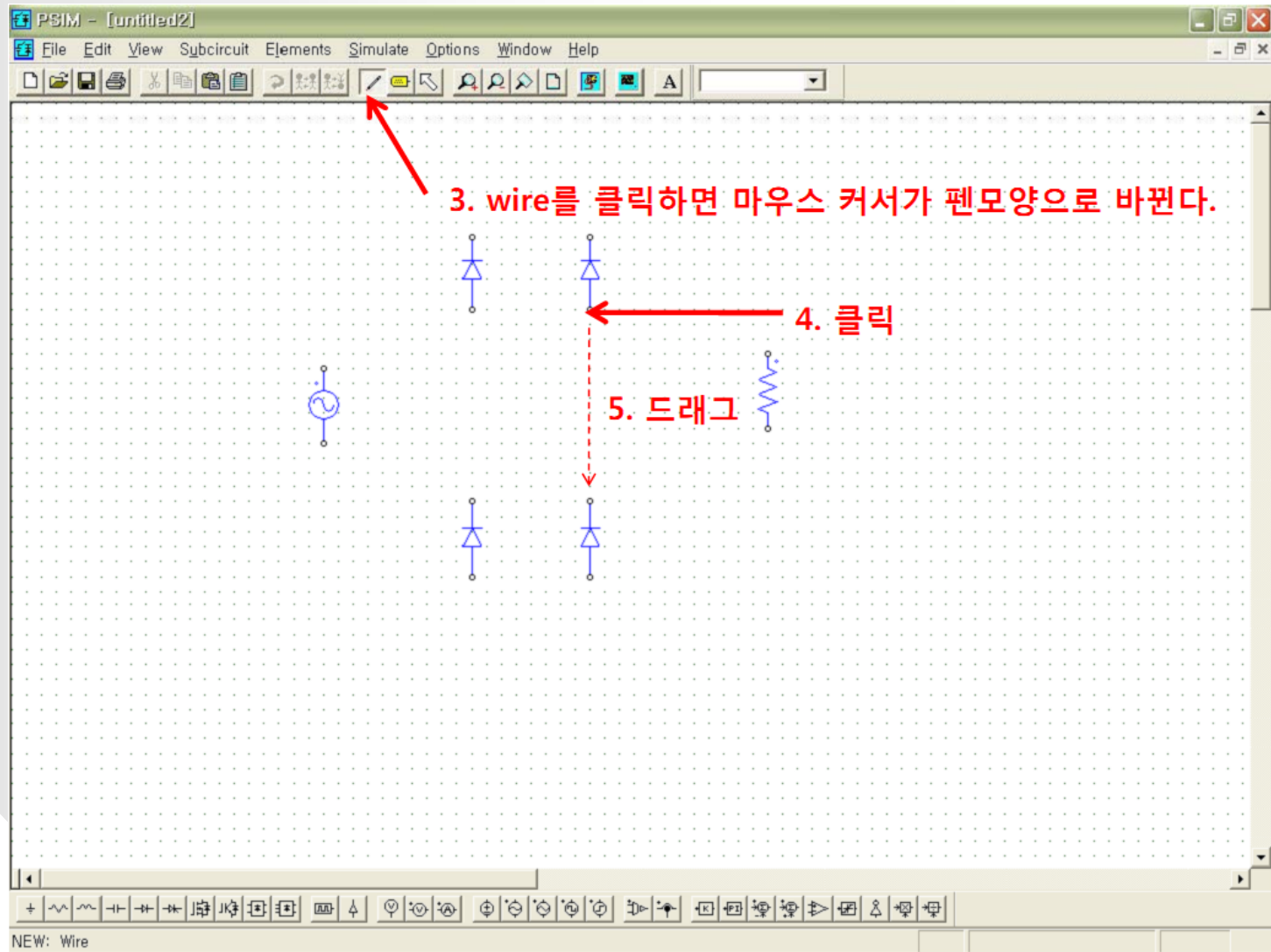


Simulation



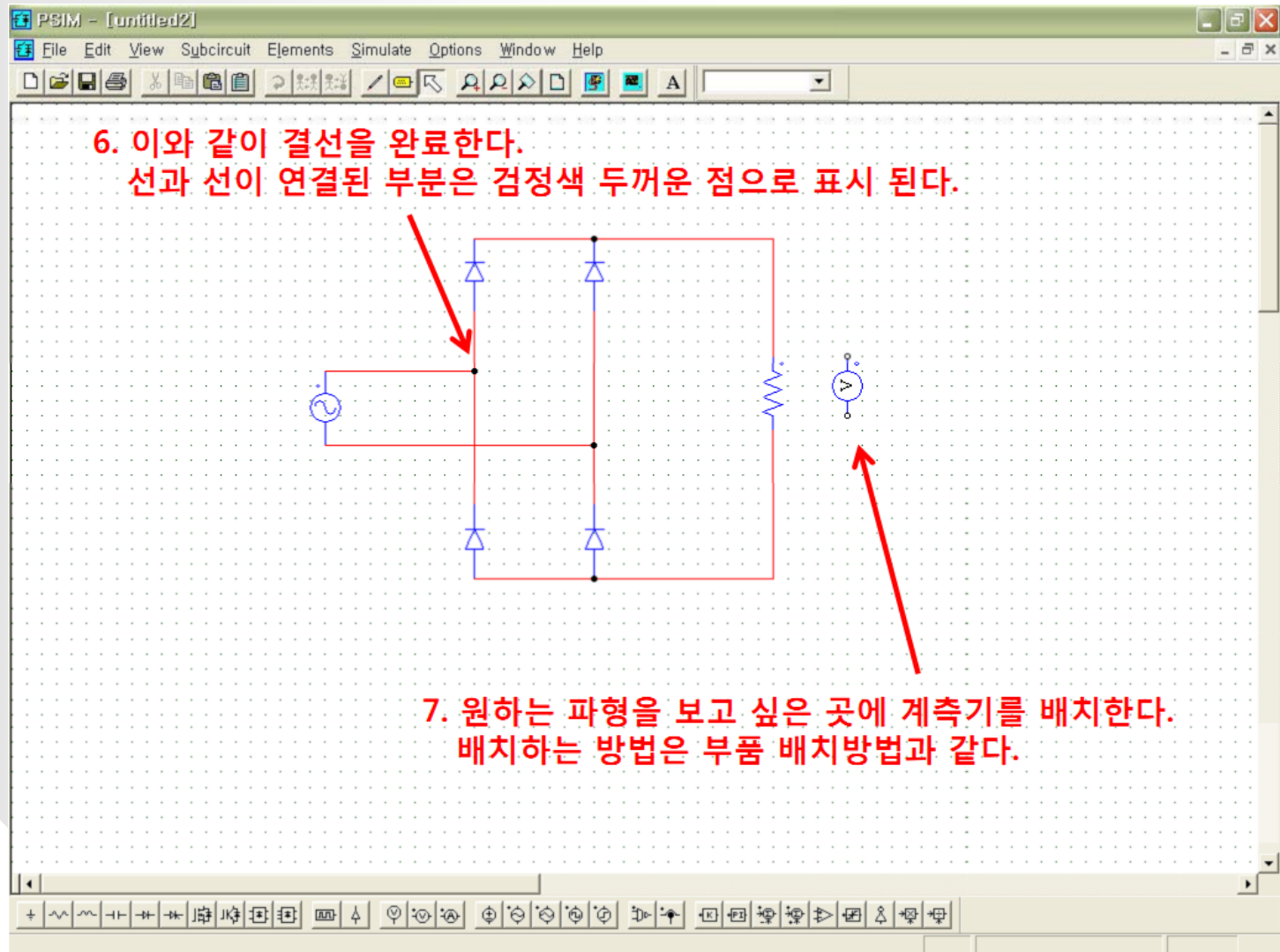


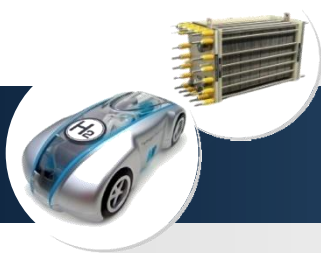
Simulation



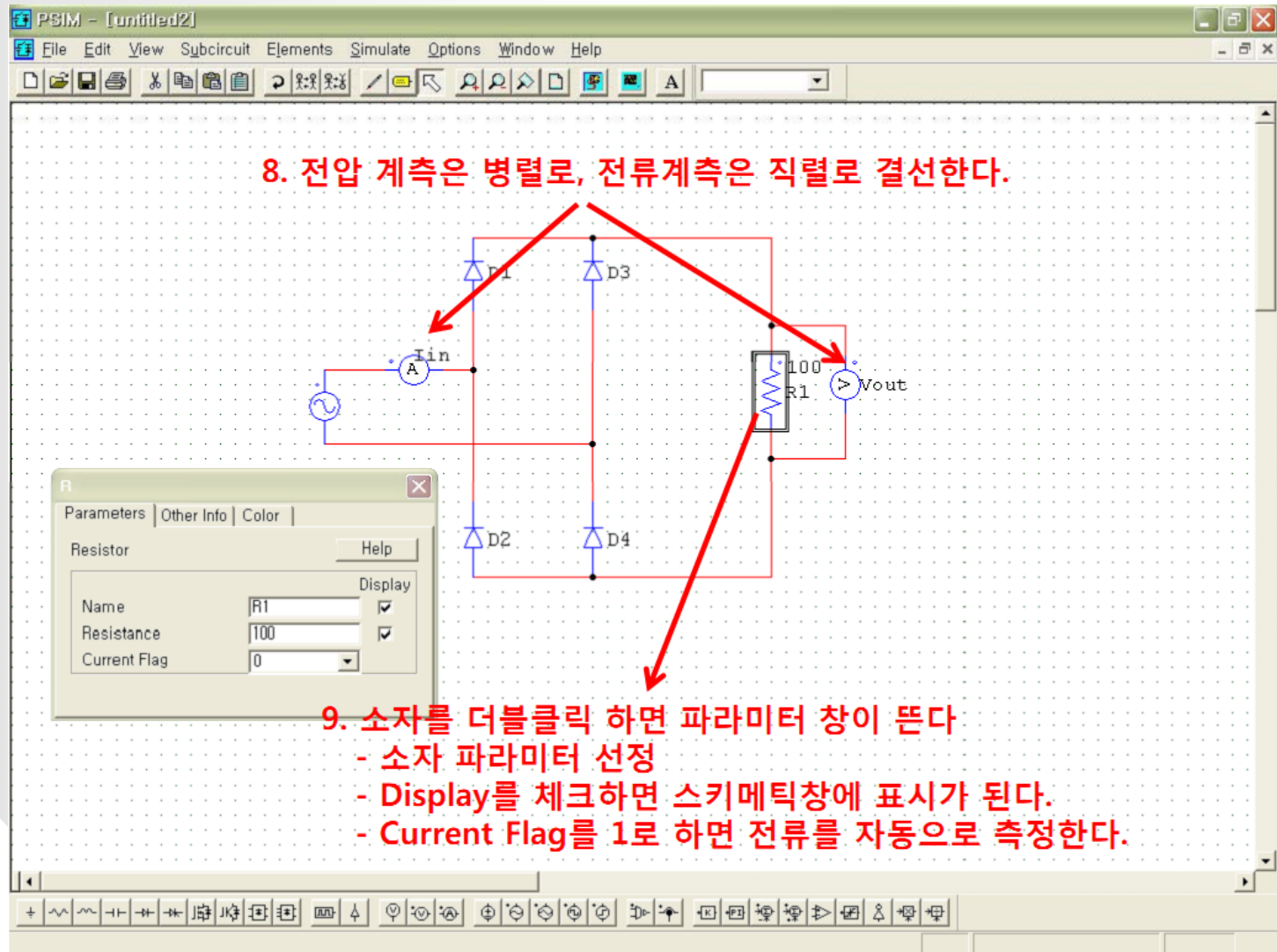


Simulation





Simulation





Simulation

The screenshot shows the PSIM software window with a bridge rectifier circuit. The circuit includes an AC source (A), four diodes (D1, D2, D3, D4), and a load resistor (R1) with a value of 100. The output is labeled Vout. The 'Simulation Control' menu is open, showing options like 'Run Simulation' (F8), 'Cancel Simulation' (Ctrl+Shift+F8), and 'Run SIMVIEW' (Alt+F8). A red arrow points to the 'Simulation Control' menu. Another red arrow points to a clock icon on the circuit. A third red arrow points to the 'Simulation Control' dialog box, which shows parameters like Time Step (1E-005), Total Time (0.01), and Print Time (0).

10. Simulation - Simulation control을 클릭

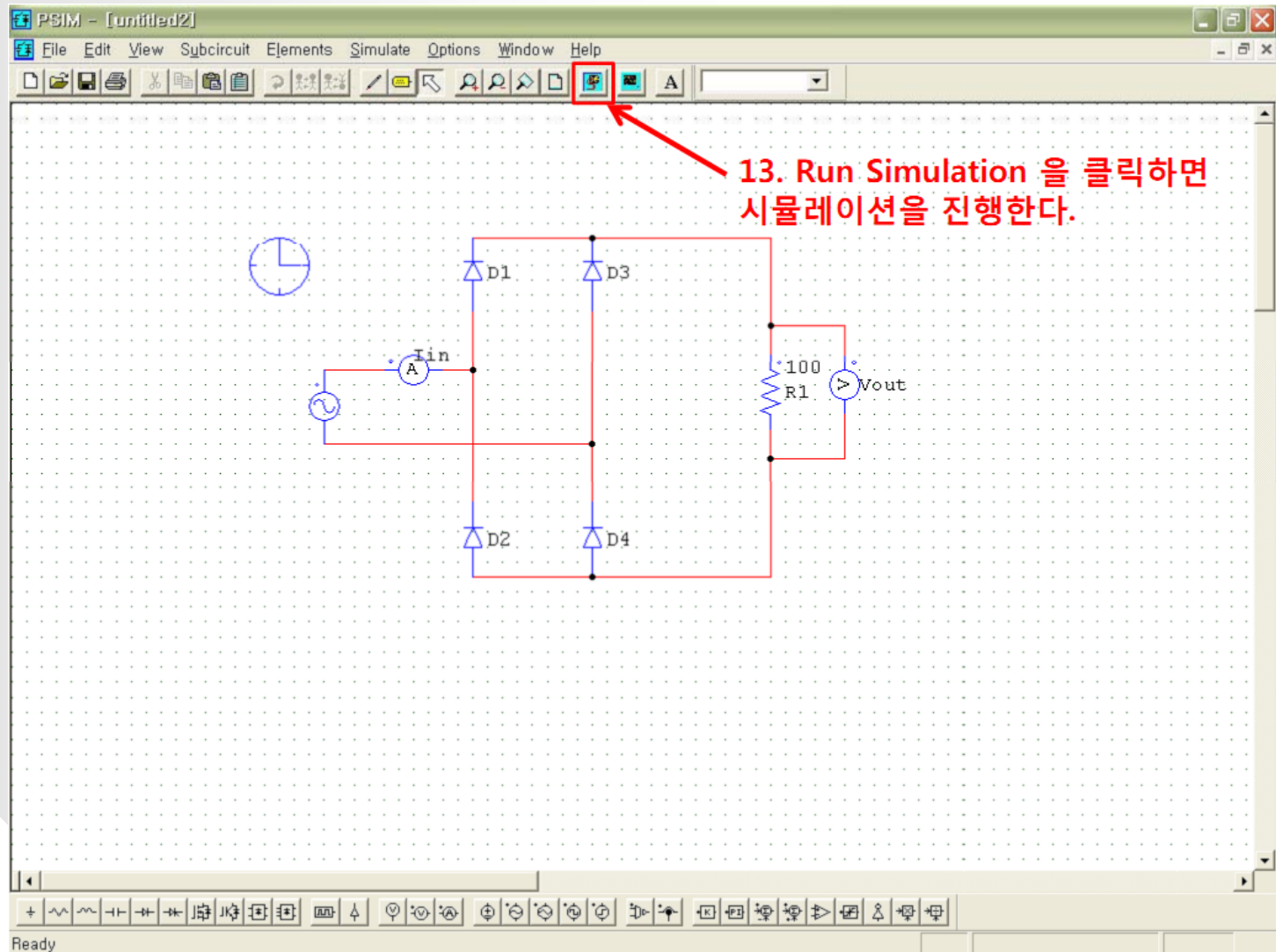
11. 마우스 커서가 시계모양으로 바뀌고 이것을 작업창의 한 부분(아무데나) 배치한다.

12. 이러한 파라미터 입력창이 뜬다.
 Time Step : PSIM의 샘플링 간격
 Total Time : 시뮬레이션의 끝나는 시간(sec)
 Print Time : 시뮬레이션의 시작 시간(sec)

Add simulation control symbol to the active document

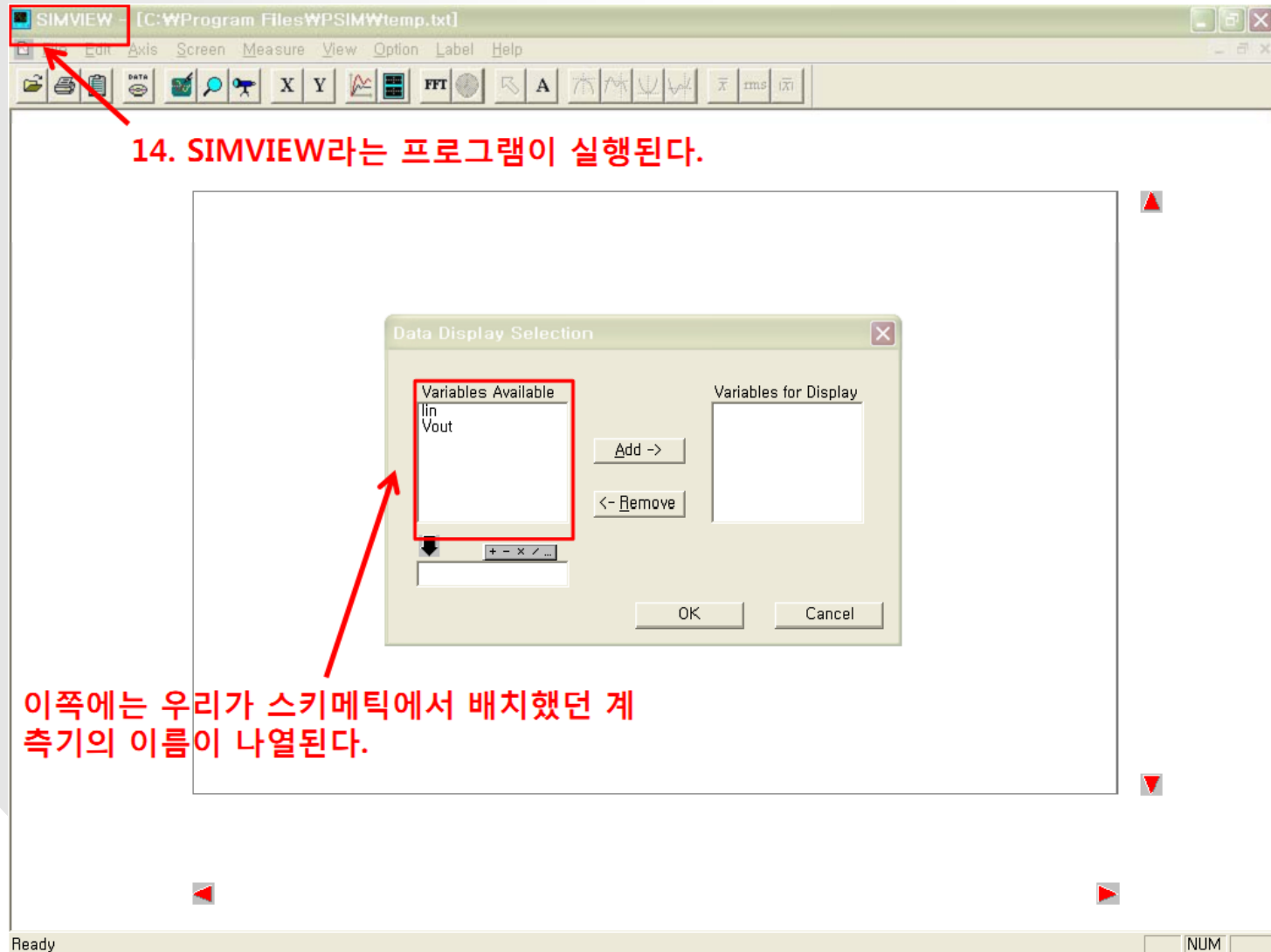


Simulation



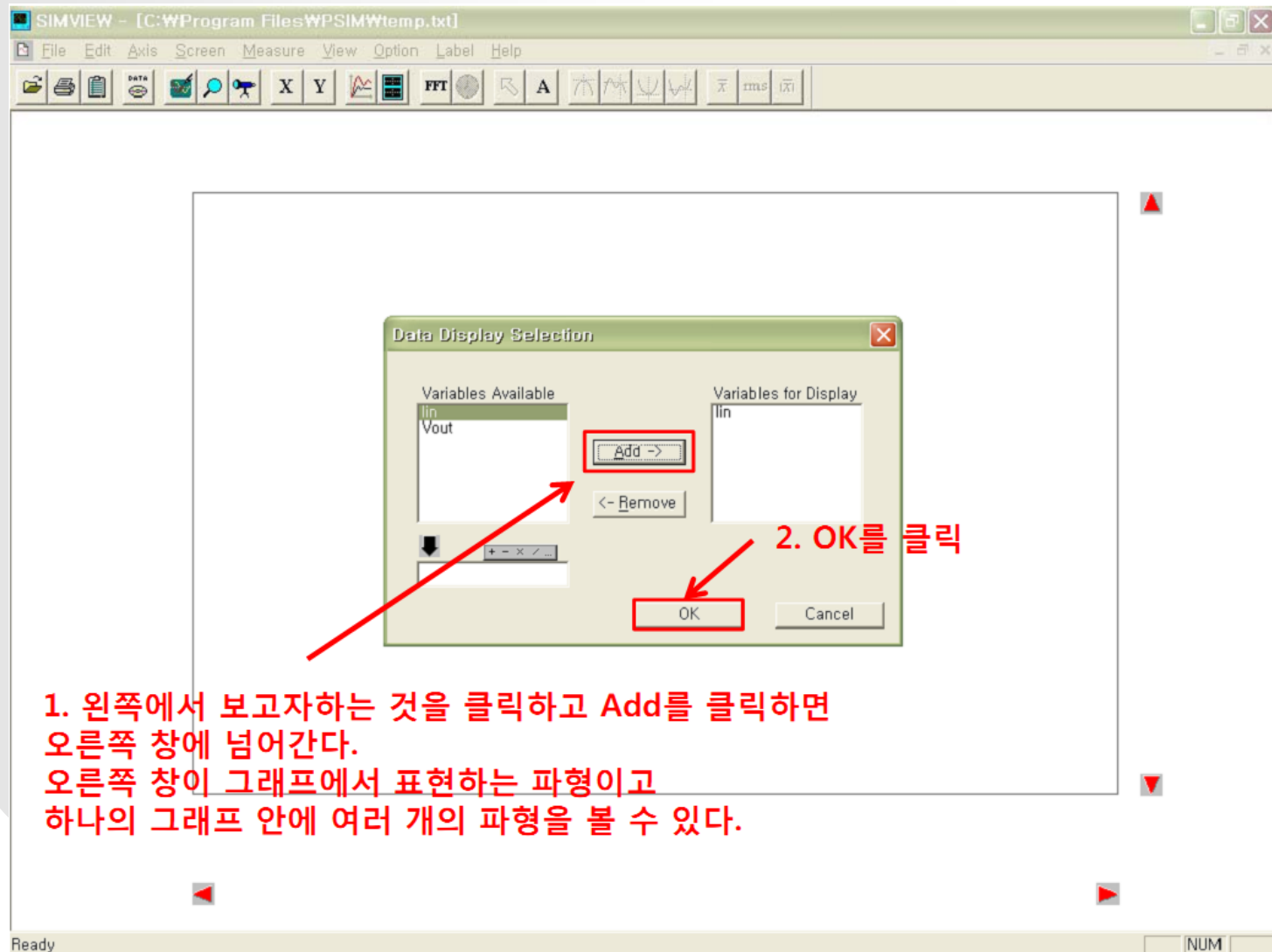


Simulation



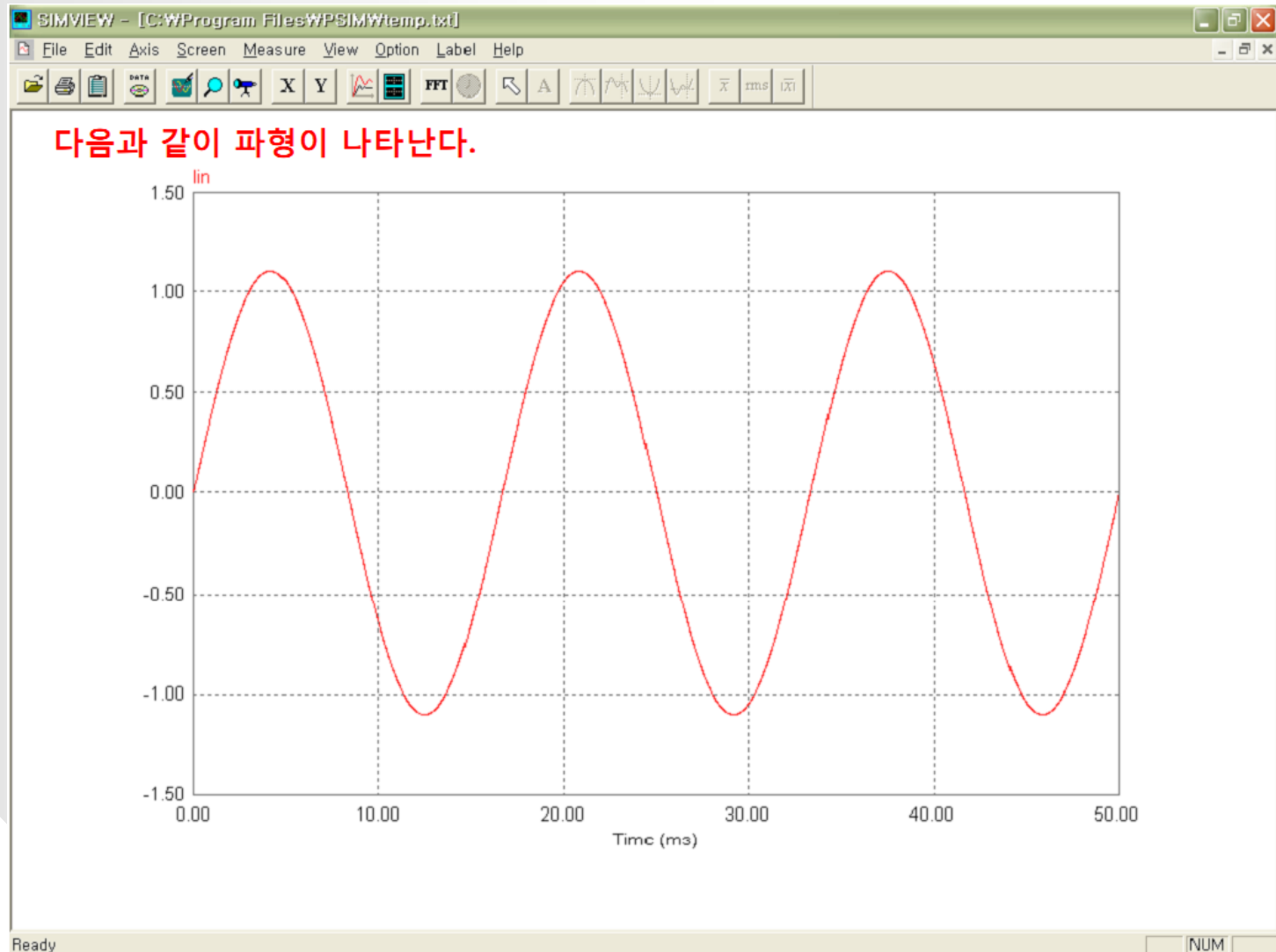


Simulation



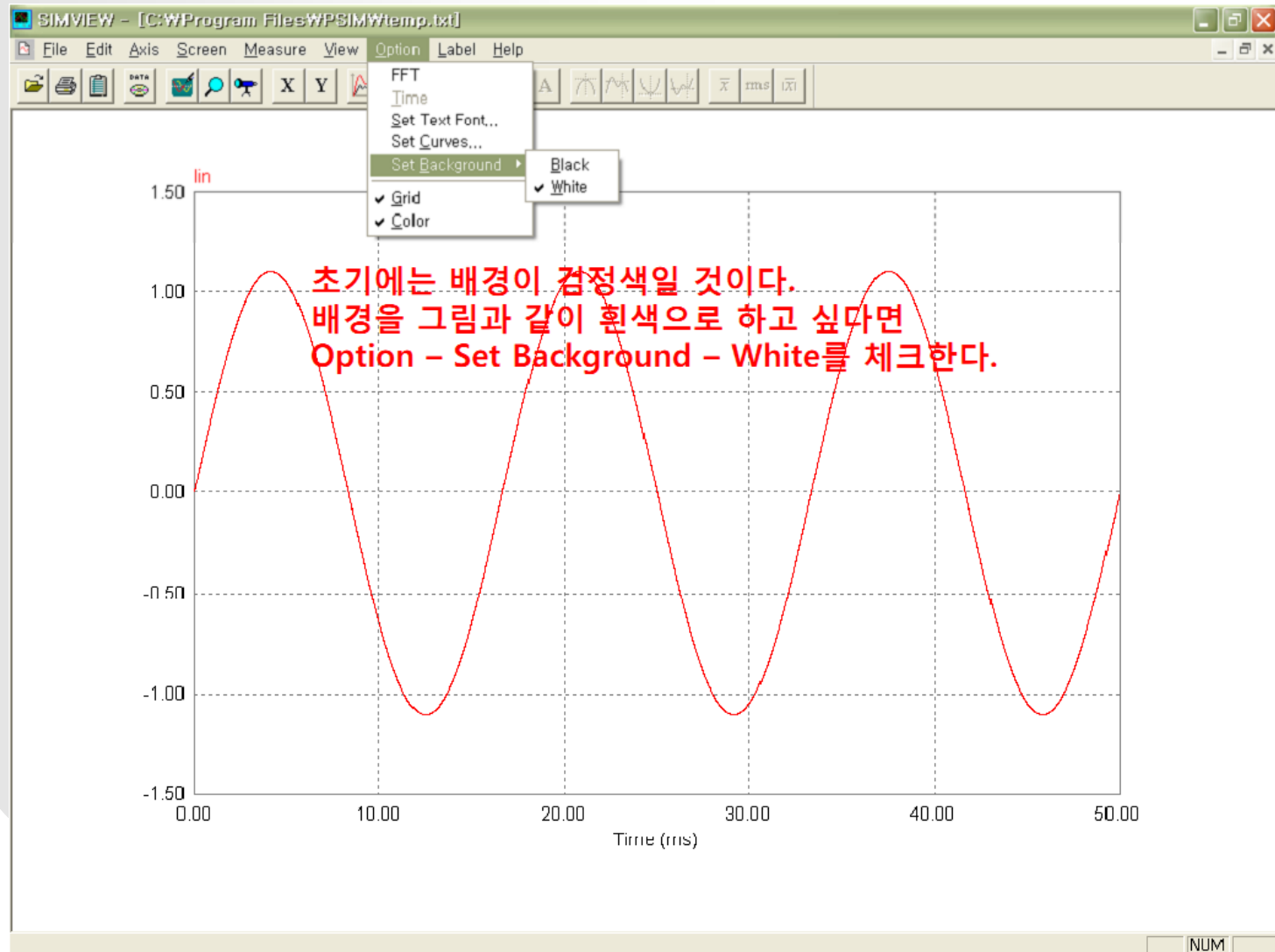


Simulation



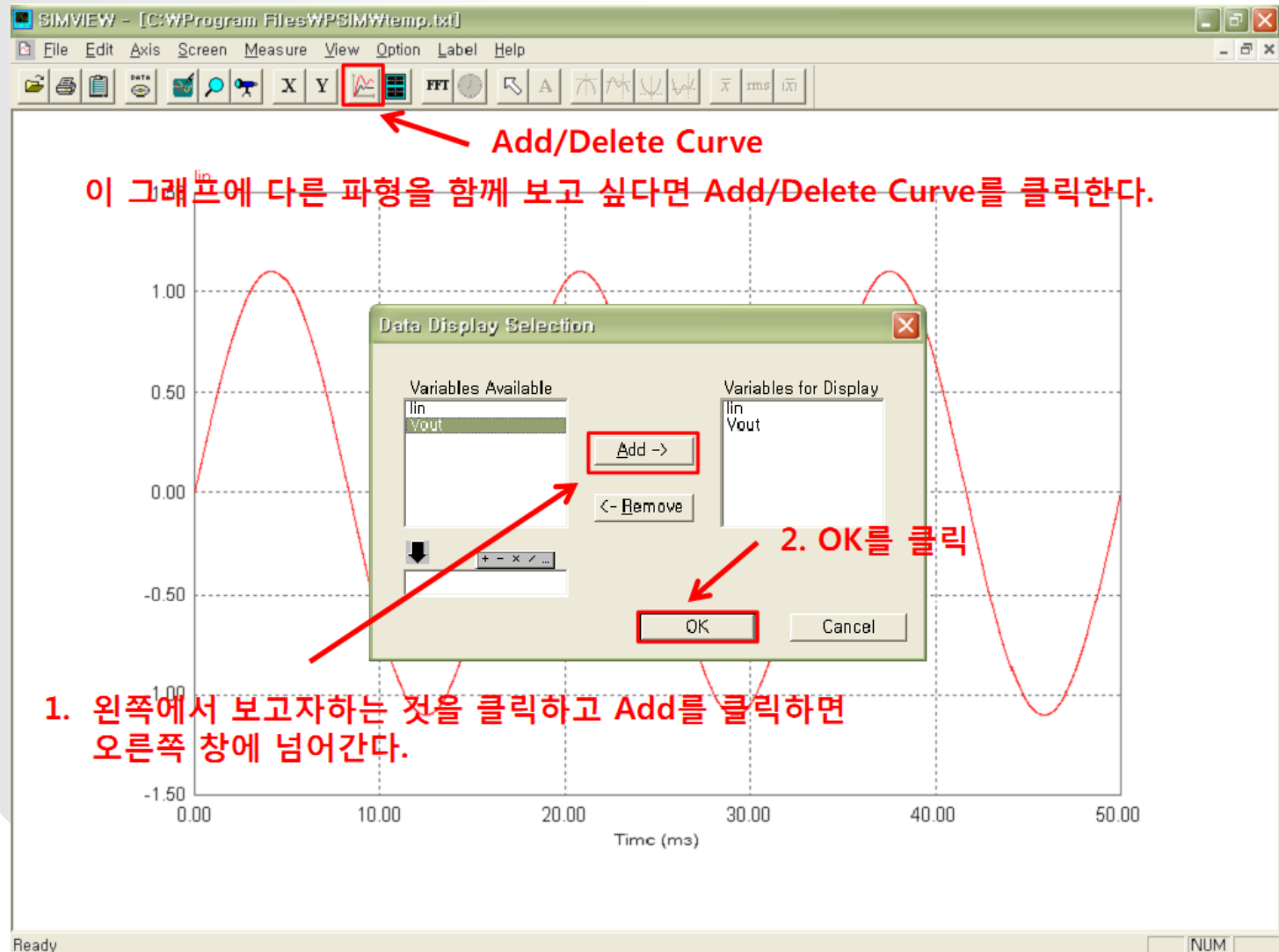


Simulation



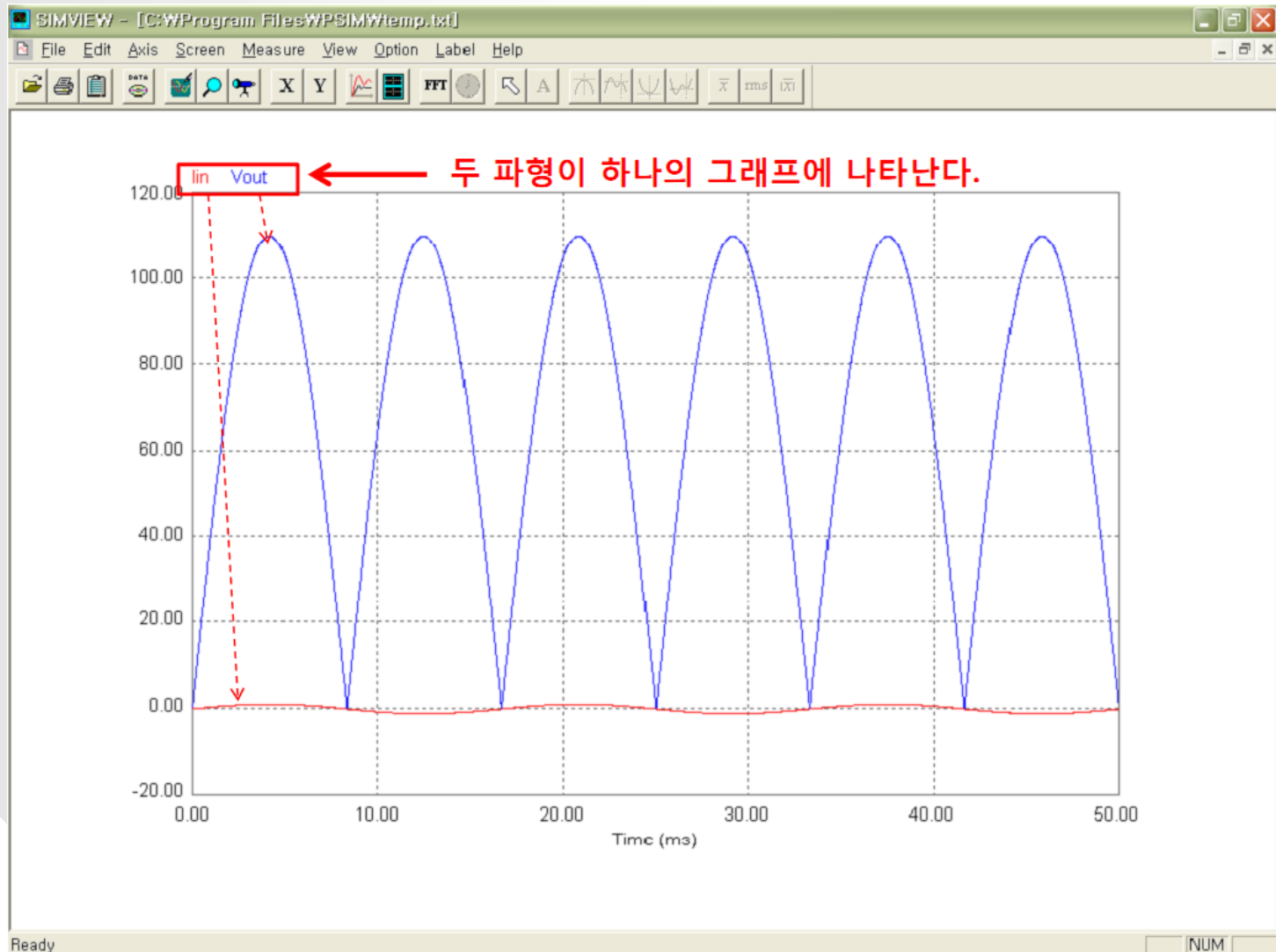


Simulation



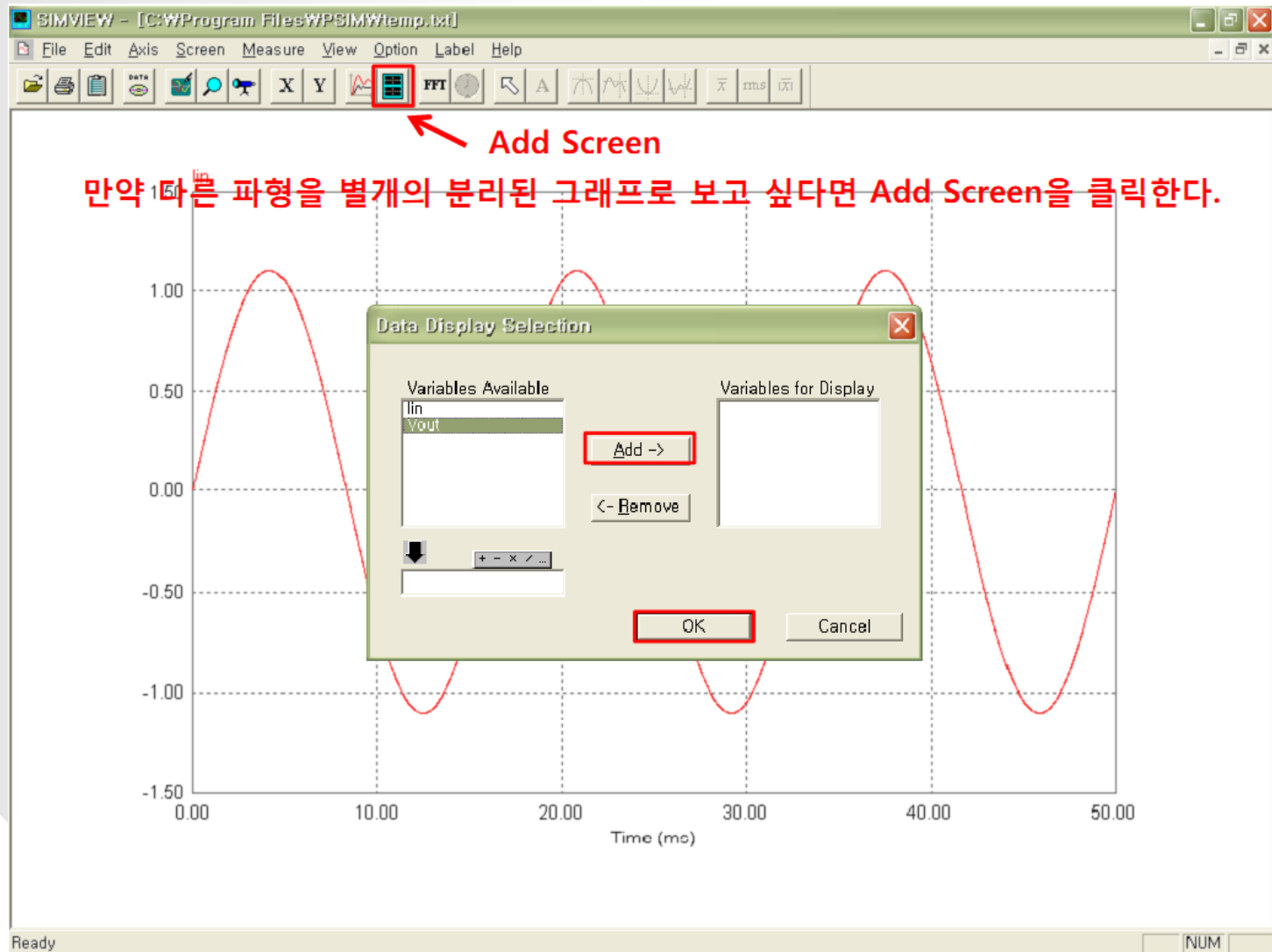


Simulation



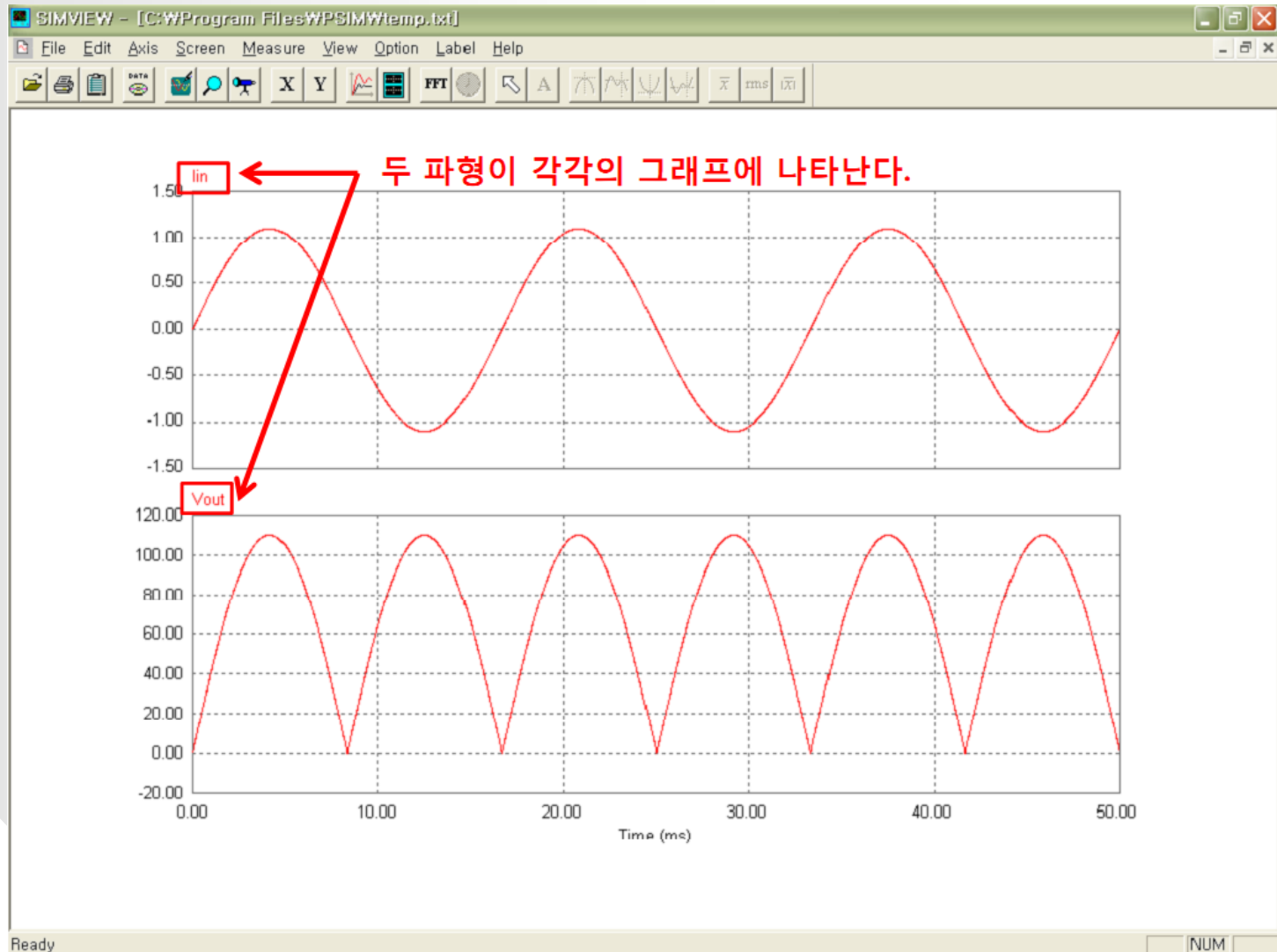


Simulation



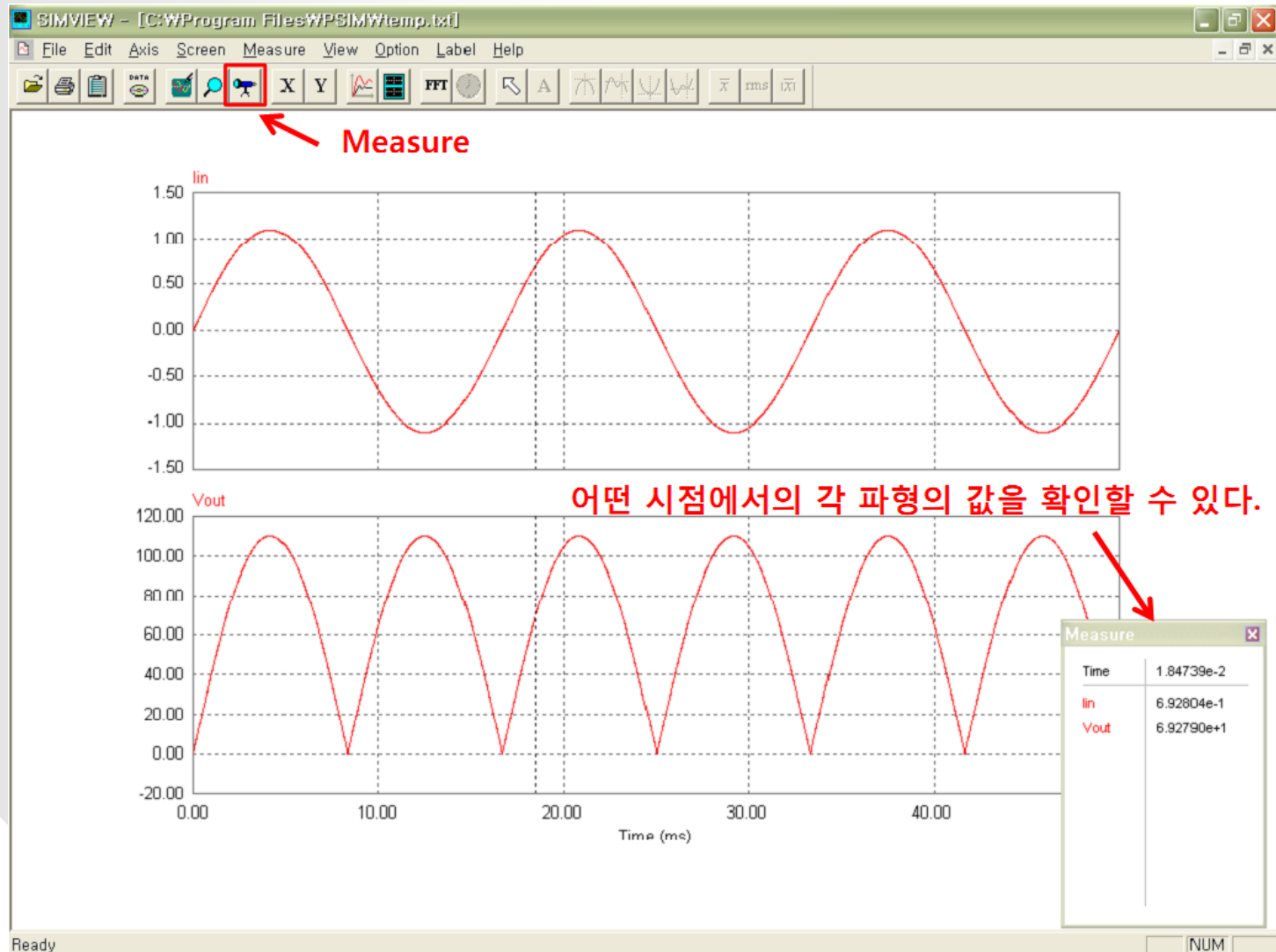


Simulation



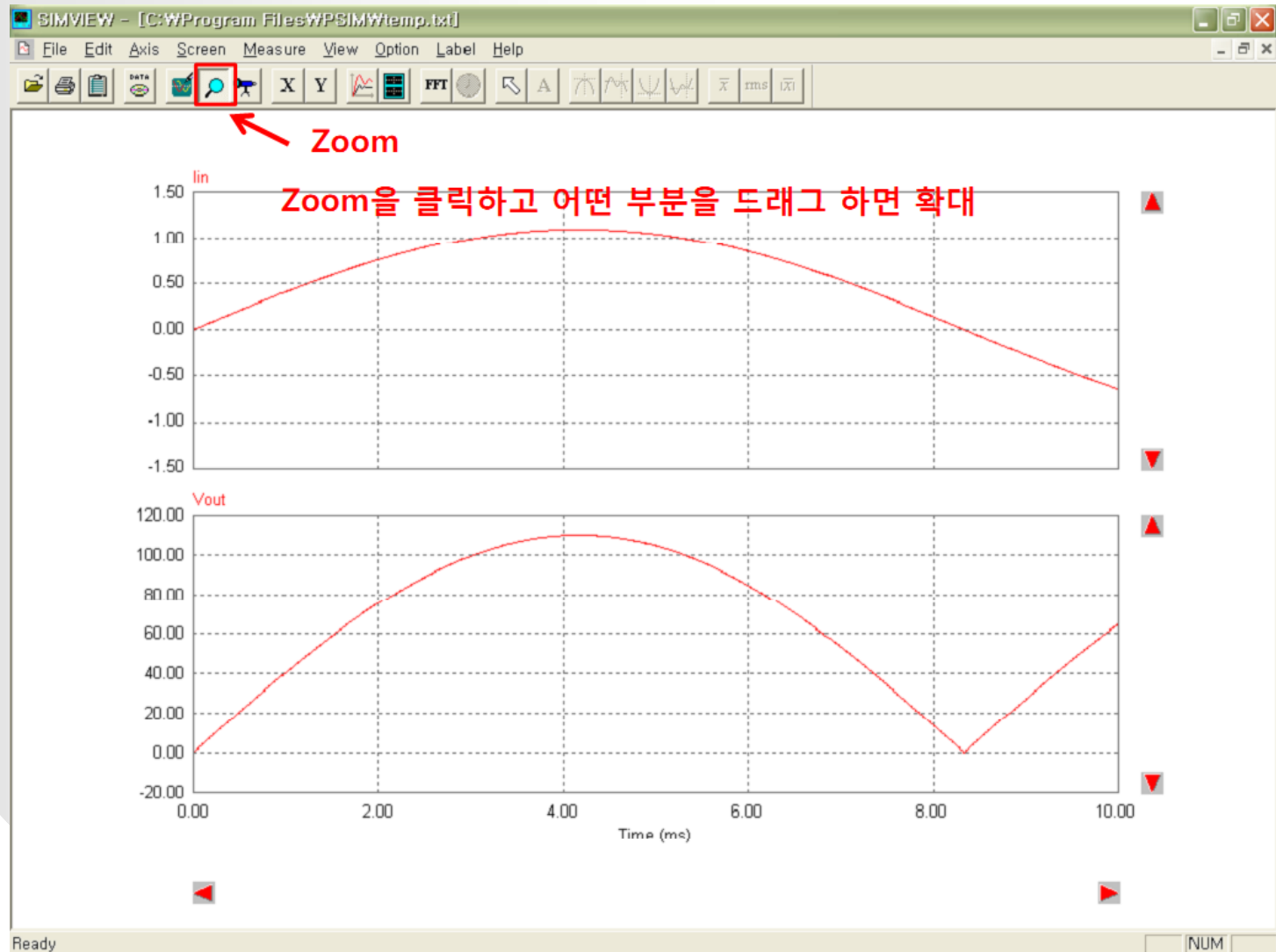


Simulation



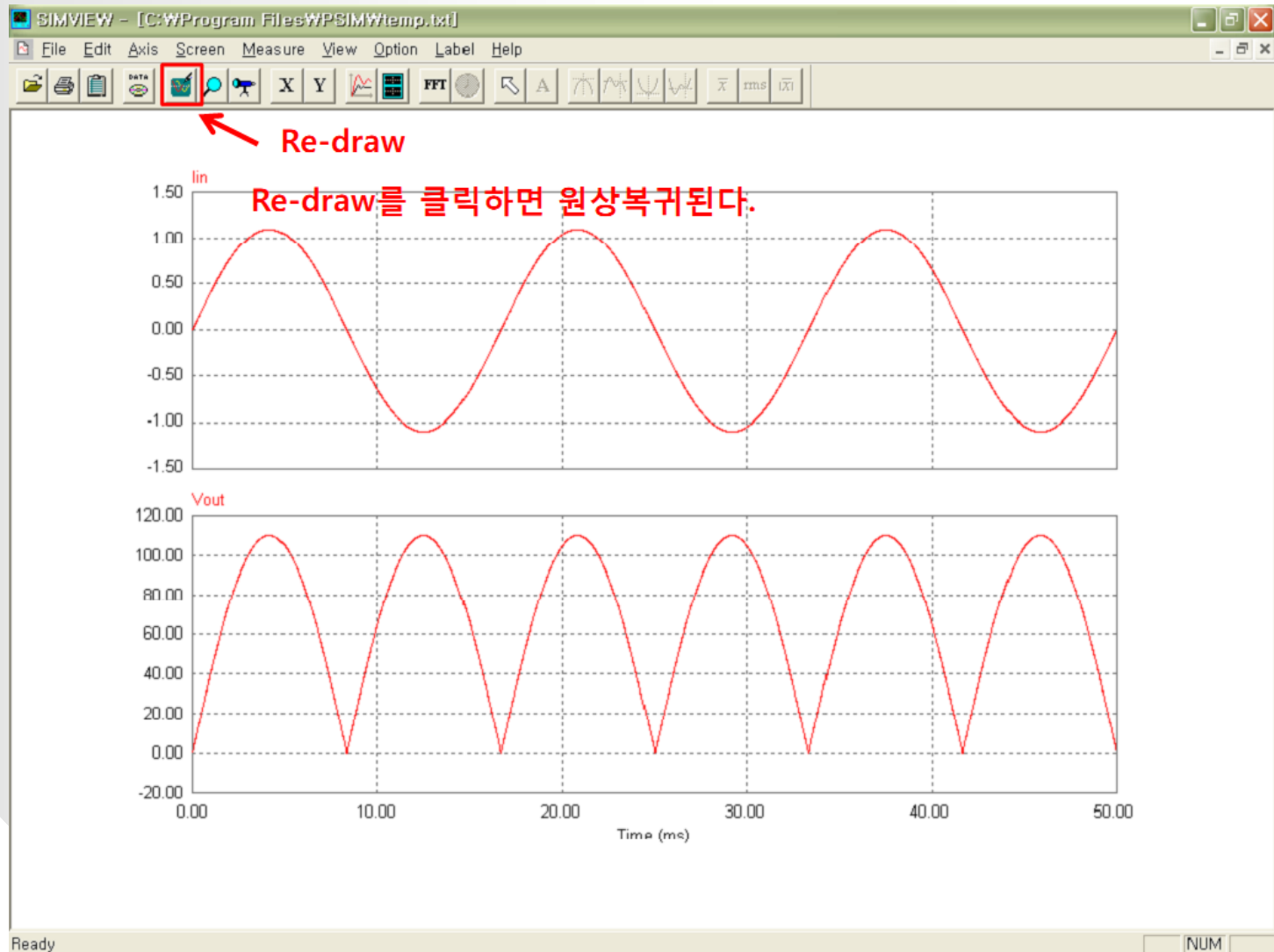


Simulation



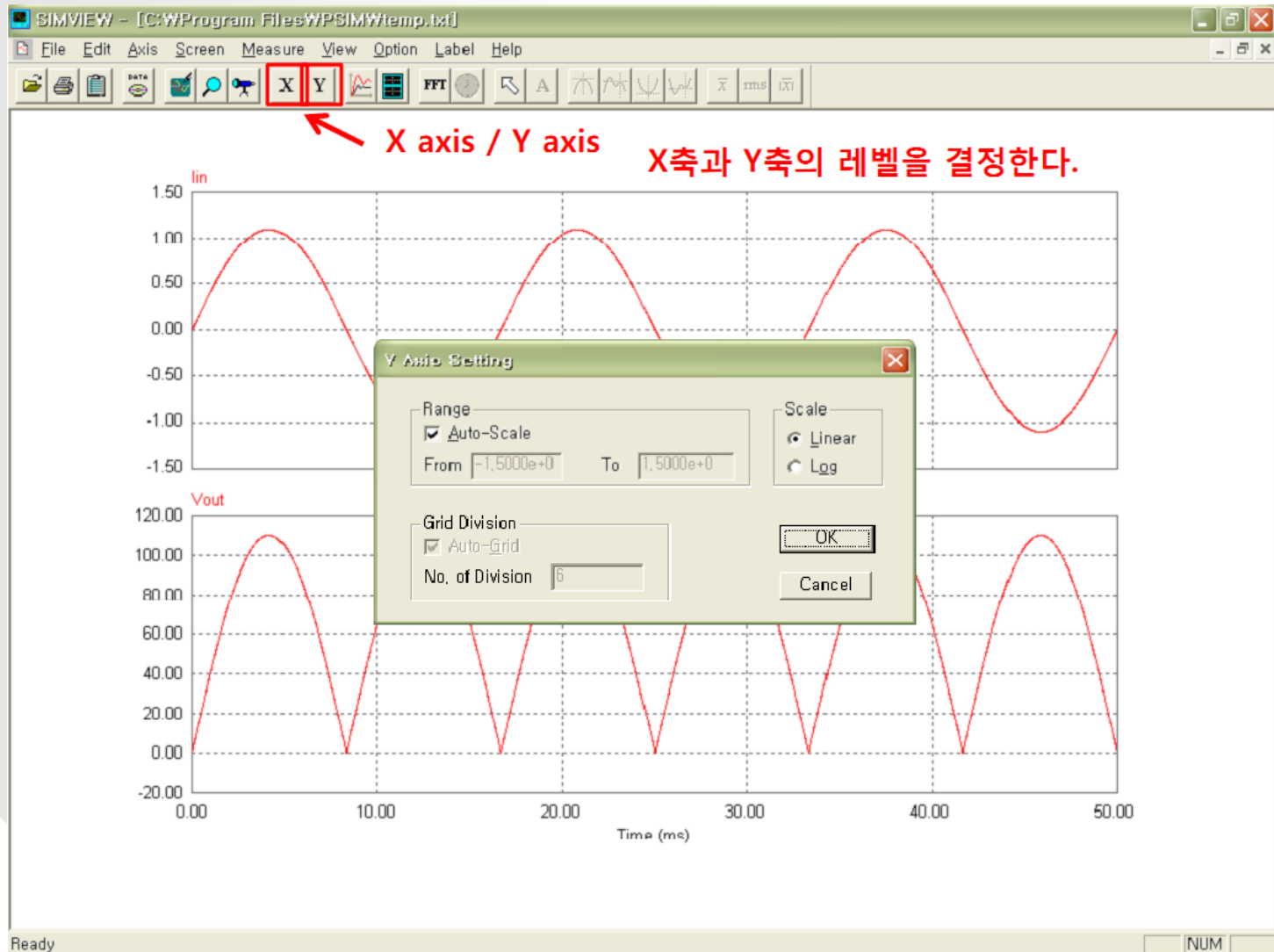


Simulation



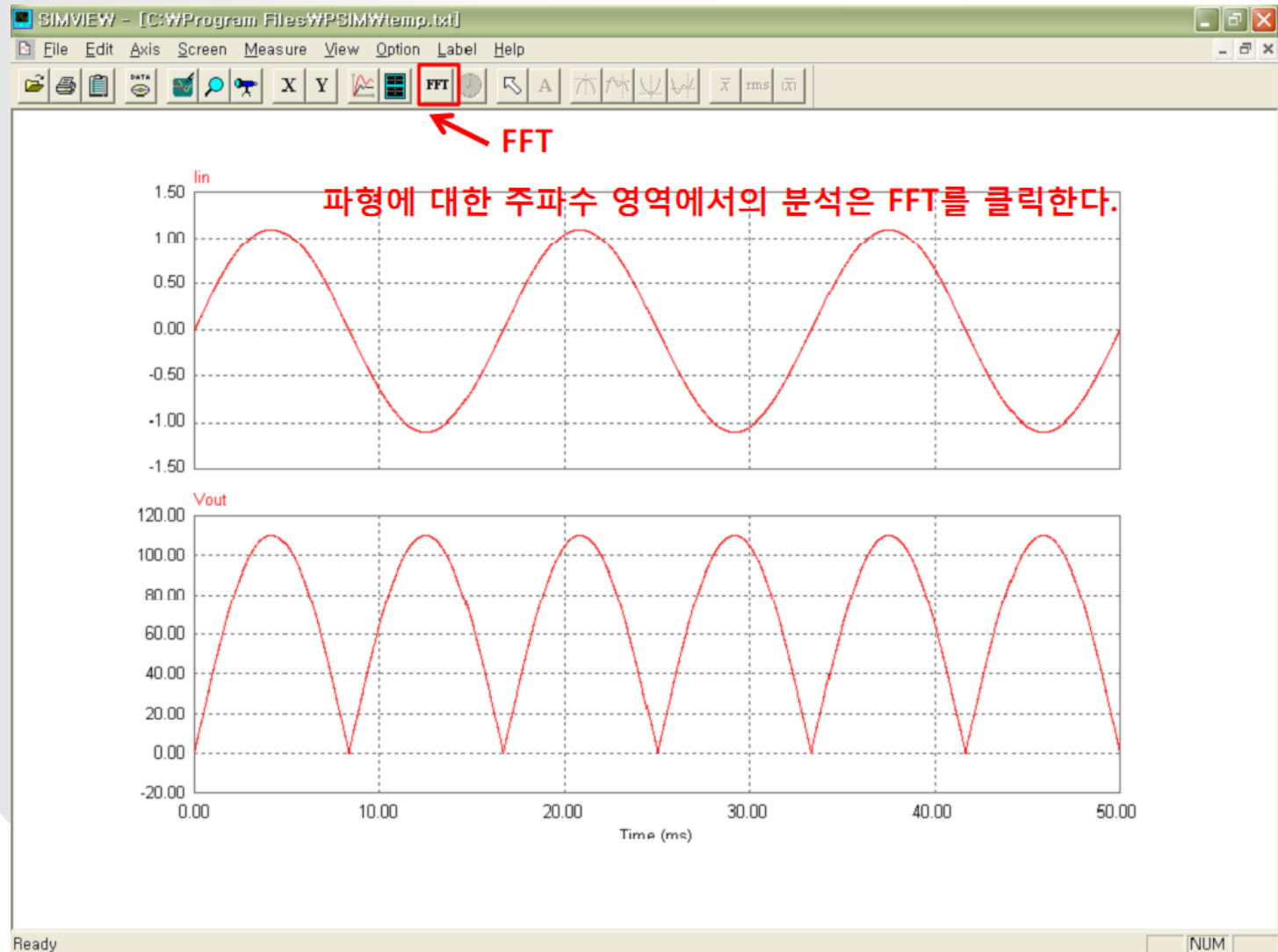


Simulation





Simulation





Simulation

